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Ultra Light Weight Solutions for Sustainable Urban Densification

城市集约化的超轻解决方案

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Maurice Hermens is working in both the Netherlands and abroad. Many of his projects are located in dense urban surroundings, underground and above ground. In the Project 'De Karel Doorman' in Rotterdam the reuse of an existing structure was the starting point: by using a smart constructive adaptation he was able to add 16 stories to an existing building.

马瑞斯·赫尔曼在荷兰和海外都有业务。他参与的大多数项目都位于城市密集区，既有地上项目也有地下项目。鹿特丹的"卡勒尔·多尔曼"大厦中对现有结构的利用是一个起点，通过巧妙的施工措施使得在现有建筑上加盖十六层公寓成为可能。

Michiel Visscher specializes in sustainable building design with a focus on material use: flexibility, reuse of existing building elements, light weight design and design for disassembly. Michiel also gained experience in complex renovation projects in crowded areas such as shopping malls, railway stations and airports where impact of construction to immediate environment often has higher priority than structural design.

米歇尔•维斯谢赫擅长可持续建筑的设计，尤其是材料的运用，专精于灵活性，再利用现有建筑，轻质结构设计以及可装配的设计。他对人口密集地区的复杂翻新项目经验丰富，比如购物中心、火车站和机场之类工程，施工对环境的影响优先于结构设计的工程。

John Kraus started as a structural engineer and became a leader of professionals. He designed many icon buildings, among which high-rise buildings with foundations on soft soil and the first outrigger in the Netherlands.

约翰·克劳斯最初一名结构工程师，并很快成为了一名领域内的领导者。他设计了许多地标性建筑，包括软土地基上的高层建筑和悬挑建筑。

Abstract

This paper shows, through the realized case project "De Karel Doorman" in Rotterdam, how ultra-lightweight solutions for apartments and other building types can be used to increase the social safety of city centers through urban densification on top of existing buildings and infrastructure. In the project 117 apartments, in 16 floors, were added on top of an existing shopping mall. This was made possible by a concept with is a combination of 1) a smart adaptation of the existing stabilizing system, which doubled the capacity of the existing columns and 2) keeping the mass to an absolute minimum using an ultra-lightweight building system. The concept can be used for building on roofs, but also above highways, railroads and on water. In combination with the ultra-low mass makes the concept also applicable in developing countries using local materials and labour, without compromising the aimed high quality and comfort.

Keywords: Ultra-Light-Weight, Building Concepts, Urban Densification, Vibrations

摘要

本文通过鹿特丹的"卡勒尔•多尔曼"大厦项目，说明了超轻型结构如何通过在现有建筑上实现城市密集化来提高城市中心的社会安全性。在该项目中，16层共117间公寓被加盖在原有的购物中心上。为实现这一构想，设计中结合了以下三个构想: 1) 巧妙地改变现有的稳定体系，从而使得柱子承载力翻倍 2) 使用超轻结构从而保证重量最小 此概念既可以利用建筑的屋顶，也可以用于高速公路、铁路、水上等建造建筑物。通过结合超轻结构，使得这一概念也可以在发展中国家使用，在不降低质量和舒适度的情况下，利用当地材料和劳动力。

关键词: 超轻结构，建筑的概念，城市集约化，振动

Introduction

Urbanism is a social geographical phenomenon which has for a long time been part of the development of society. The intensity fluctuates in time, but cities keep growing. With ever scarcer building space, we have seen many examples in the recent past of densification at locations not seeming suitable for building. Sometimes existing buildings and infrastructure are being demolished, some buildings are built over existing city fabric and some buildings are built through existing buildings. While densifying cities, those examples all share loss of functionality, damage to historic and cultural aspects and loss of valuable resources.

In the city of Rotterdam the 'De Karel Doorman' project shows that urban densification can be achieved by activating unused load bearing potential of existing heritage structures. By using ultra-light-weight building concepts the released potential creates a five times higher density than traditionally possible. Not only has the business case become viable, vertical urbanism becomes possible at places where it wasn't before. Furthermore existing

简介:

城市集约化已经成为了社会发展中的一个由来已久的城市地理现象。城区的密度并不是恒定的，时常会随着时间波动，但总体仍保持上升趋势。而由于缺少建造建筑的空间，在许多本不适合建筑的区域出现了许多城市密集化的例子。有时现有构筑物被拆除，一些建筑物被建造在原有建筑之上甚至内部穿过原有建筑。在城市集约化的过程中，这些建筑都在丧失他们的现有使用功能和历史文化价值。

在鹿特丹"卡勒尔•多尔曼" (De Karel Doorman) 项目中，城市的集约化通过"激发"原有建筑的承载能力来实现。通过超轻建筑的概念，我们可以实现传统方式五倍以上的城市密度。不仅有了更多商业的可能性，我们也可以在原本无法做到的地方建造垂直城市。此外，现存的建筑与基础设施依然可以在施工期间继续使用并保持完整。可见，这一概念在很多全球性的大城市中提供了许多的可能性。

背景:

我们提出了一系列垂直扩建的设计方案，接下来我们将简短地描述已知的一些方法。(见图1,2)

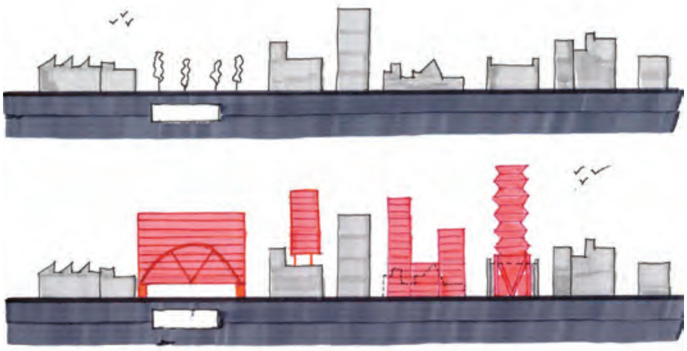

Figure 1. Urban densification concepts (Source: Royal HaskoningDHV)
图 1. 城市集约化 (来源于 Royal HaskoningDHV)

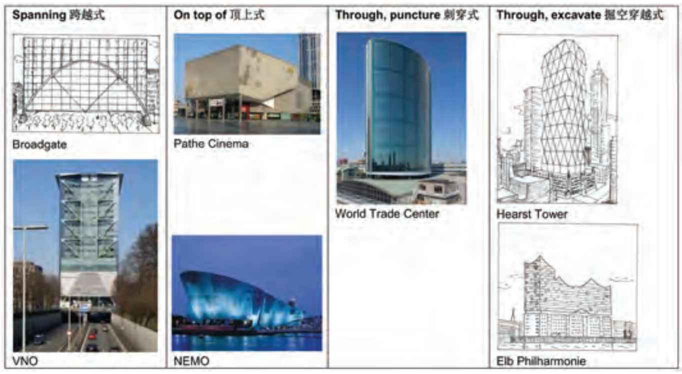

Figure 2. Urban densification examples (Source: Royal HaskoningDHV)
图2. 城市集约化的例子 (来源于 Royal HaskoningDHV)

buildings and infrastructure can remain intact and in use during construction. The concept offers lots of potential in cities and metropolises around the globe.

Context

We recognize a range of different design solutions for vertical extension. Below we will shortly describe the known types (see Figure 1 and 2).

Spanning Other Buildings and Infrastructure

This type of densification we see where (underground) infrastructure is present. The area in the sky is available for densification, but foundations in the ground cannot be made. At buildings like Broadgate London and the VNO office building in The Hague the lack of space for the foundation is solved by a bridge-like superstructure spanning the infrastructure. Typical aspects of these extensions are expressive structural architecture, high concentrated forces at foundation level, and coordination with the existing urban structure to prevent damage and control differential settlements. These buildings often require higher investment.

Building Through Other Buildings and Infrastructure

This type of densification we come across when there is a wish to keep the pre-existing buildings combined with the need to expand at the same location. Parts of the existing building are kept, and part of the building is demolished to create space for the extension. The bandwidth in creating space varies from punctures through the existing building to create space for large columns and a core (like the WTC Rotterdam) to complete excavation of the existing building remaining only the façade (like Hearst tower in London and Elb Philharmonie in Hamburg). Typical for extensions through existing buildings is the need for a new superstructure and own foundation. The interior of the pre-existing building and its functional use always changes dramatically or vanishes completely. The existing building will never be the same again, valuable resources are thrown away, and if we continue this type of vertical extension of densifying cities, we keep diminishing cultural and historical aspects of buildings, streets and cities.

Building on Top of Other Buildings and Infrastructure

This type of densification we often see at smaller scale: one or two stories are added to a building. Structures often have some residual capacity that can be used. These small scale extensions do not lead to real densification, because the size of extensions is not large enough.

1.跨越其它建筑或构筑物

在这种密集化的方式当中，现有建筑是原本就存在的。这片区域的上层空间可以被集约化化利用，不过我们无法在地上建造建筑的基础。伦敦的德盖特大厦 (Broadgate) 以及海牙的VNO办公大楼，他们的地基问题是通过让桥型的上层结构跨越原有建筑来实现的。这种延展的方式为了防止损坏和不均匀沉降，往往有着富有特色的建筑结构，很高的集中应力以及和现有建筑相互协调作用。这种构筑方式往往成本较高。

2. 穿越其它构筑物

在我们希望保留原有建筑，同时希望在原有基地扩建的时候，我们会采取这种集约化的方式。原有建筑会被部分保留，而另一部分会被拆除从而为扩建腾出空间。 方法上，既可以为柱子或者核心筒腾出空间在原有建筑中间开洞 (如鹿特丹世贸中心)， 也可以挖空原有建筑而仅保留立面 (如伦敦的赫斯特塔和汉堡的Elb Philharmonie) 。扩建时，往往需要让上部建筑及其基础穿越现存建筑。因此，原有建筑的内部功能往往会改变甚至彻底失效。现有建筑将不再是原来的样子，它的价值也消失殆尽。如果我们一直进行这样的城市集约化，城市、街道、建筑的历史文化将会逐渐丧失。

3.于原有构筑物之上建造

这种集约化的方式常见于小尺度的改造，比如对原有建筑进行一两层的加层改造。建筑的结构往往有一些剩余承载力。因为这种改造的尺寸不大，所以这些小尺度的扩建不会带来真正的集约化。

改造的下一步，就是利用剩余承载力。比如，高速公路隧道的设计足以抵御水压力和侧向土压力。伦佐•皮亚诺设计的位于阿姆斯特丹的NEMO博物馆，就是在这样一个隧道之上建造的。桩中的合力由拉力转化为压力，而之前用于承担侧向力的墙，可以承担增加的重量。因此，也就不需要建造额外的基础。鹿特丹的Pathé电影院就是建造在一个地下停车场上面。原本停车上上方的覆盖层被轻质结构替代，新剧院的结构选用了钢混结构。因此，不再需要额外建设地基基础。

工程实例: 卡勒尔•多尔曼大厦

鹿特丹的卡勒尔•多尔曼大厦运用了上述的最后一种工法，但是做了很大了改进。整个结构的侧向力和竖向力被分开，从而提高了体系的竖向承载力。

设计方法也迥然不同，成为了一个"反向设计"。原有建筑结构的尺寸和质量是恒定的，而建筑的强度通过计算和测试得到。实测承载力与设计荷载之差就是所允许增筑的重量。通过结合超轻结构的概念，被释放的承载力可以使得建筑更加集约化，而现有建筑和城市设施的历史文化价值也不会有损失。

A step further in this process, is to make use of hidden structural capacity. For instance: a highway tunnel is designed to withstand upward water pressure and lateral soil pressure. The NEMO museum, designed by Renzo Piano, in Amsterdam is built on top of such a tunnel. Resulting forces in the piles transform from tension to compression and the walls previously laterally loaded, can take the added weight in compression. No additional foundation was needed. The Pathé cinema in Rotterdam is built above an underground parking garage. The heavy finishing of the former square is removed and replaced by light weight structure. A steel and composite structure is used to create the cinema theaters. No additional foundation was required.

Realized Case 'De Karel Doorman'

The "De Karel Doorman" project in Rotterdam builds on the last mentioned extension type, but makes a large step beyond: the hidden structural capacity is actively created by smart modification of the structural system: separating the structural system for lateral forces from the system for vertical forces increases vertical bearing capacity.

The design approach changed dramatically: reverse structural design. The structural sizes and material quality are there: the existing structure. How strong the building is, is determined by calculations and testing. Subtracting the design load of the existing building from the tested capacity gives the weight of the extension that can be added. Combined with an ultra-light-weight building concept, the released capacity can be used to create high densification without the loss of value of pre-existing buildings and city infrastructure. Also the high impact on the immediate environment reduces substantially.

Architectural History and Motive

During World War II the city center of Rotterdam was almost completely destroyed. In the years after the city center was rebuilt. The building called Ter Meulen (see Figure 3) was designed by Dutch architects Van den Broek & Bakema in the famous Dutch modernistic style. It was realized between 1948 and 1951. Originally shops were placed in the basement, the ground floor and the 1st floor. The 2nd floor was housing offices and the canteen. This floor was intended to be used as a salesroom too in the future. In that case the offices and canteen would be replaced to a new-to-be-built 3rd floor. In the structural design of the pile foundation and the superstructure this expansion was already taken into account. The design comprised an open floor plan made possible by a structural system of columns and beams providing lateral stability, so no structural walls were necessary.

In the late '70's two (instead of one) extra floors were placed on top of the original building. This was possible by using relatively light weight floors. However during the '90's the retail marked changed and the formula of shops decayed more and more. Especially the 2nd floor and above became empty.

New Destination

The owner asked Dutch architect Ibelings van Tilburg to investigate the possibilities for this location: demolition and new construction or preservation of the existing building in a new context. Because of the few (modern) monuments existing in the city center, the architect chose for the 2nd option. Their suggestion was placing a large block of apartments above the building (see Figure 4). Through this urban densification the liveliness of the city center was to be enhanced, especially in the evenings.

Figure 3. The original building 'Ter Meulen' (Source: Royal HaskoningDHV)
图3. 'Ter Meulen'的老楼 (来源于 Royal HaskoningDHV)

建筑的历史与动机

二战期间，鹿特丹市中心几乎被完全摧毁，之后许多年才得以恢复。荷兰建筑师Van den Broek & Bakema设计的Ter Meulen大楼 (图3) 建造于948至1951年，是荷兰现代主义的名作。起初，一层和二层是商店，三层有办公室以及食堂。同时，三楼也有以后作为卖场使用的规划。如果改造的话，三楼的办公室和食堂将被搬到新建的四楼。因此，原有的结构设计已经在地基基础部分的承载力考虑了这样的扩建。梁柱结构体系提供了侧向稳定性，使得楼层平面得以开放，因此不再需要结构性的墙体。

在70年代末，原有结构上被加盖了两层。这是通过使用轻型楼板来实现的。然而90年代末零售业的凋零导致商店倒闭，二楼及以上几乎完全空置。

新目标:

业主希望荷兰建筑师Ibelings van Tilburg探索这块基地的可能性，是拆除重建还是通过一种新的方式保留原有建筑。 由于市中心罕有现代的纪念性建筑，建筑师选择了第二种方式。他们建议在原有建筑上加盖一桩大型公寓 (图4) 。由于城市集约化，市中心的热闹程度会增加，尤其是在晚上。

真正的挑战在于如何利用现有的柱子和桩基结构体系，在现有建筑上加盖16层公寓的情况下保持原有建筑完好

解决方案:

解决方案通过综合以下三种方式来实现:

分析现有结构的承载体系，及其已知或未知的承载能力

对于新建上部公寓采用超轻型建筑体系

分离水平荷载和竖向荷载

分析建有建筑的结构体系

现有数据: 现存建筑的资料十分齐全，包括自重计算，稳定性计算，混凝土尺寸，配筋计算以及配筋图。此外还有桩基布置，场地勘测报告，桩基安装及测试报告，以及桩基建造日程表。

现有承重结构体系: 现有结构体系为现浇混凝土。梁柱通过钢架作用提供侧向稳定性。柱网为8x10m。柱子在每一层的尺寸相似，地下室大约直径850mm圆柱，以上大约直径800mm圆柱。抗压强度设计值为250kgf/cm^2，根据欧洲规范大致相当于C14/17 (棱柱实验强度C17，立方体实验强度C17) 的混凝土。主梁尺寸600 x 850 mm，设计抗压强度200 kg/cm^2。

The challenge was to keep the existing building as original as possible, by adding the new 16 stories with apartments truly on top of the existing building, using the existing load bearing system of columns and pile foundation.

Solution

The solution to this question was found by a combination of three approaches:

- The analysis of the load bearing system and its existing and unrevealed load bearing capacities.
- Using an ultra-light weight building system for the new apartment building on top.
- Separation of the vertical load bearing from the horizontal load bearing.

The Analysis of the Load Bearing System of the Existing Building

Available Data. The existing building was well documented: gravity load calculations and stability calculations, concrete dimension and reinforcement calculations and drawings of reinforcement were available. Also the pile plan, the geotechnical survey and advice and a report on the installation and testing of a test pile were available, together with a calendering drawing of the installation of the piles.

Existing Load Bearing System. The load bearing system was completely cast-in-situ concrete. The columns and beams did provide the lateral stability of the building through rigid frame action. The column grid was 8 x 10 meters. Because of the rigid frame action the columns are almost similar in dimension on all floors: round 850 mm in the basement to round 800 in the 2nd floor. The intended compression strength of the columns was 250 kgf/cm^2, which can be compared to a C14/17 strength according to Eurocode. The main beams are 600 x 850 mm with an intended compression strength of 200 kg/cm^2.

Existing Foundation. The foundation was designed with reinforced prefabricated concrete piles, with a shaft dimension of square 380 mm and a + shaped pile tip of 760 mm. The calendering showed that there had been a great amount of soil densification due to the installation of the piles: in a group of 8 piles the last 25 blows on the pile caused a settlement of 200 mm in the first, down to only 40 mm in the last pile of the group. This was a strong indication that the bearing capacity of the piles was much larger than the originally intended 70 tons (or 900 kN according to present codes).

Tests. First inspections (visual and with a Schmidt Hammer) indicated that the quality of the construction and thus the concrete strength was very good. In combination with experience and literature the first starting point was a present concrete strength of C28/35 for the columns. In a later stage cylinders were drilled and tested from 18 different columns, giving a real concrete strength of even 40,9 N/mm^2.

To be able to recalculate the capacity of the existing piles as accurate as possible new cone penetration tests (CPT's) were made, inside the building right next to the pile groups, thus measuring the soil densification: the load bearing capacity according to present codes was 1.600 up to 2.000 kN.

Structural Design of the New Apartment Block

Load Bearing Capacity of the Existing Building. The solution for the challenge to place the 16 stories truly on top of the existing building

现有基础: 基础为钢筋混凝土预制桩，为边长380mm的小方桩以及十字形760mm的桩头。进程表显示，由于桩的压实作用，土壤变得很密实。一组8根桩当中，最后25下的锤击在第一根桩中引起了200mm的沉降，在最后一根中则将至40mm。这很好地说明了桩基承载力远大于设计值70吨 (或根据现有规范: 900KN) 。

测试: 根据检测 (视测法以及混凝土回弹仪) ，混凝土质量优良。根据经验和相关文献，可初步推测现有混凝土柱强度为C28/35 (棱柱实验强度C28，立方体实验强度C35) 。之后根据对18根不同柱子的钻芯实验检测，得到混凝土实际强度为40.9 N/mm^2。

为了将现有的桩基的承载力核实的尽量准确，在建筑内部的桩基应用了一种新的CPT测试，通过测量土壤的压实度，得到了承载力从目前法规要求的1.600提升到2.000KN。

新公寓的结构设计

现有结构的承载力: 实现原有建筑上16层加盖的方法为: 为分离在原有建筑和加盖层的水平荷载和竖向荷载，新增了两个截为面7x9m，墙厚0.4m的核心筒。核心筒与原有建筑刚性连接，从而提高了原有楼板的承载力。

因为刚架作用，现有结构由于水平荷载，在梁柱当中都有弯矩。改造后系统变为柱子仅承受竖向荷载 (见图5) 。通过对弯矩的估测，柱子在不需要任何结构变动的情况下，承载力从5.000KN增加到了10.000KN。

公寓最大重量250Kg/m^2 (单位面积，总重) ，极限活荷载为175 Kg/m^2，其它层活荷载为70 Kg/m^2 (根据荷兰规范，荷载分项系数0.4) 。这5000KN的承载力足以承受额外16层的重量。桩群的承载力为8x1.600KN=12.800KN，高于新的设计荷载。

柱网选用4 x 6 m。加盖部分底层的连梁把柱网的荷载导向原有建筑8 x 10 m的柱网。

由于核心筒的稳定性不好，轻质结构存在因为风荷载而倾覆的可能。因此新建核心筒下的基础底板为10 x 16 m。所有的新桩都被设置在基础底板边缘，从而防止拉力达到使用极限。桩的拉力强度极限达到600KN，故桩群需要埋入地下超过25米。

现有建筑的验算:

不均匀沉降: 原有建筑的柱网有三列，而加盖层只占两列，因此会导致柱间25mm的沉降差。这些变形会导致梁柱内的弯矩增大 (偏心弯矩) 。但经过计算发现，这些弯矩小于支撑柱子所需要的最小弯矩 (根据结构规范) ，因此不需要减少竖向承载力。

配筋验算: 因为翻新工作，原有的几处梁板柱被移除。经过比对，这些地方的配筋和图纸中的配筋相比完全相同，且状况良

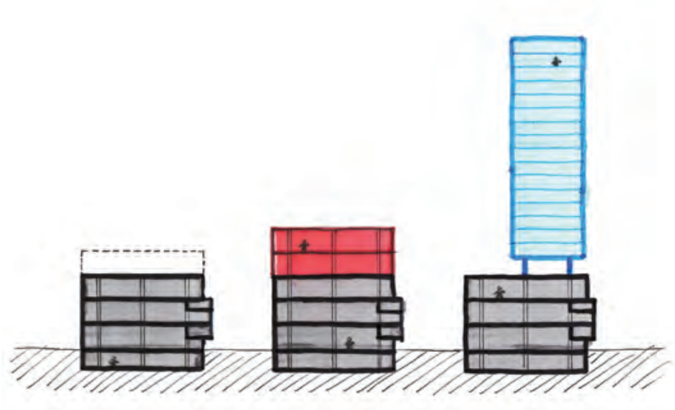

Figure 4. Development of building Ter Meulen (Source: Royal HaskoningDHV)
图 4. Ter Meulen的建造过程(来源于 Royal HaskoningDHV)

was found by separating the horizontal loads from the vertical, for the new expansion as well as for the existing building: 2 concrete stability cores were added (for staircases, elevators and ducts) with a section of 7 by 9 meters and wall thickness of 0.4 meters. These were not only used for the new building, but also the floors of the existing building were rigidly connected to the new stability cores.

In the existing building the structural load bearing system thus changed from a system with rigid frame action, with bending moments in the beams and columns caused by horizontal loads, to a system with supported columns, only having to carry vertical loads (see Figure 5). By eliminating those bending moments the load bearing capacity of the columns increased from about 5.000 kN to about 10.000 kN without any structural modification of those columns.

With a weight of maximum 250 kg/m^2 for the apartments (all inclusive, per GFA) and an extreme live load of 175 kg/m^2 on one floor and 70 kg/m^2 on all other floors (load combination factor 0,4 according to Dutch Code), it was now possible to realize the 16 within those extra 5.000 kN. The pilegroups had a new load bearing capacity of more 8 x 1.600 kN = 12.800 kN, which was more than the acting design force in the new situation.

The optimal column grid for the new apartment building was chosen to be 4 x 6 meters. In the lowest new floor steel transfer beams in two directions are used to transfer the new column grid (perimeter columns and middle columns) to the column grid of 8 x 10 meters in the existing building.

With the small footprint of the stability cores and the lightweight structure overturning uplift due to wind loads could be likely. For that reason the foundation plate below the new stability cores is 10 x 16 meters. All new piles have been placed near the perimeter of the foundation plate. In that way tension forces in Serviceability Limit State were prevented. In Ultimate Limit State the tension forces in the piles are up to 600 kN, for which the piles are placed deeply into the sand layer more than 25 meters below ground level.

Additional Checks of the Existing Building
Differences in Settlements. The new block is placed on only two of the three existing column lines, causing differences in settlements up to 25

好。

假设分析: 敏感度分析用于不可预见的关键部位钢架单元缺失。计算结果显示剩余安全性满足要求。同样对于断桩，也进行了相同的计算，满足要求。

以上验算保证了结构工程师和保险公司不需要承担不必要的风险。

高舒适度要求的轻型结构体系
结构体系: 为了把重量控制在承载力范围之内，16层的公寓只能重量不能超过250 kg/m^2。这仅仅相当于荷兰住宅规范设计值得五分之一。在荷兰建筑声学性能要求很高，因此为避免业主投诉，声阻将超过政府标准10dB。

所以超轻结构按如下顺序建造 (见图6) :

-钢梁和钢柱

-木质楼板上加55mm厚混凝土面层

-公寓单元之间采用双层轻钢龙骨石膏板隔墙

-木质外隔墙

-玻璃板外墙面

盒中盒: 为实现公寓内每户之间的隔声，建筑的设计使用了盒中盒的概念。木梁和钢梁之间用橡胶弹簧分割。公寓内不同房间的楼板和墙也彼此独立。天花板为悬挂式。通过以上措施，每一间公寓都和周边住户间有很好的隔声性能 (水平方向和竖向) 。

隔声性能与振动传播: 为了实现以上高标准的隔声性能，公寓的房屋单元和钢结构之间是完全弹性支撑。不过，这样的系统很容易在同一层传传递振动，引发不适感。总的来说增加声阻 (约20-30 Hz) 的解决方案会增加可感的振动 (小于10 Hz)的传播。

公寓内行人振动的目标值大约为0.1 mm/s (单步，几何均方根，90%有效统计值) (见图7)

楼板振动性能的建模，测试与校正: 由于很难精确预测特定的振动频率，而这些频率又对振动水平的预测影响很大，因此，计算中采用了动力有限元实际比例模型。

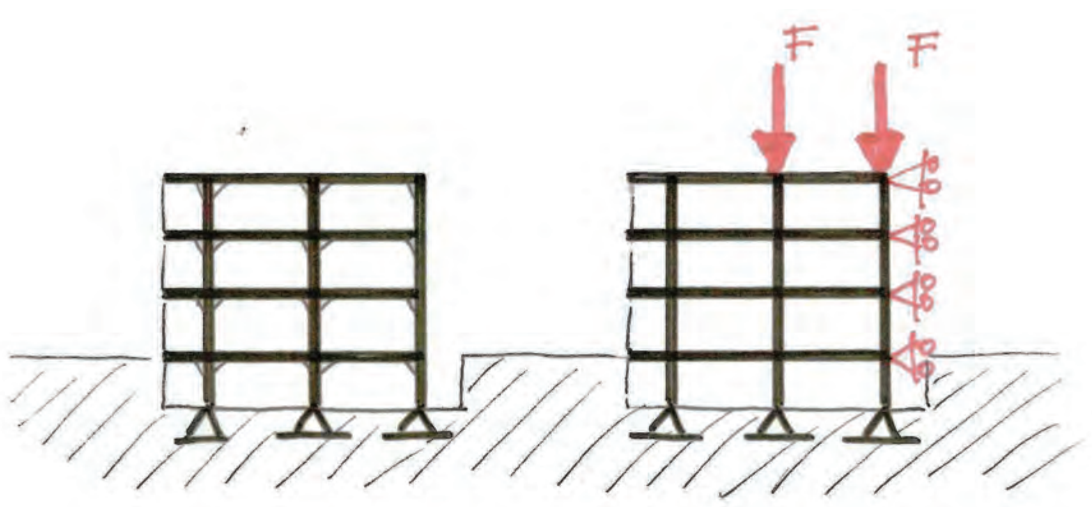

Figure 5. Structural stability scheme before and after (Source: Royal HaskoningDHV)
图 5. 改造前后的结构稳定性分析 (来源于 Royal HaskoningDHV)

mm between the columns. These implied deformations cause bending moments in the beams and thus in the columns. These bending moments were calculated smaller than the minimum required bending moments in the supported columns (in conformity with the structural code), so they did not reduce the vertical capacity.

Check of Existing Reinforcement. In several places parts of existing columns, floors and beams were removed because of the renovation. In all those places the found reinforcement was compared with the original drawings. No deviations were found, giving good confidence in the original construction.

What-if Analyzes. Sensitivity analyses were performed for the unforeseen situation in which reinforcement would be (partly) absent in crucial elements like columns and piles. The residual safety was calculated to be sufficient. The same was done for the case of broken piles in a pile group, with the same positive result.

This all together was enough confidence for the structural engineers in the original building and also for the insurance company to be able to insure the new building without running disproportional risk.

Light Weight System with High Demands for Comfort

Structural System. In order to stay within the available (released) load bearing capacity, the 16 apartment floors can weigh only 250 kg/m2. That is roughly 1/5th of the weight of standard Dutch concrete apartment buildings. The acoustic isolation demands however are very high in the Netherlands and in this case a value of 10 dB higher than the governmental demands is used in order to prevent user-complaints.

Therefore the ultra-light-weight structure is built up as follows (see Figure 6):

- steel columns and beams
- wooden floor system with a 55 mm concrete topping
- a double separated metalstud and gypsum wall system between the apartments
- a wooden façade (exterior wall)
- glass cladding on the outside

Box-in-Box. Every apartment is acoustically separated from the other following the box-in-box principle. The wooden beams are isolated from the steel beams by rubber springs. The floors of the different apartments are separated from each other. The walls between the apartments are also separated and the ceiling is suspended. In that way every apartment is acoustically isolated from its neighbors (vertical and horizontal).

Acoustic Isolation vs Vibration Transfer. In order to reach the above mentioned high demands for acoustic isolation, the apartments are completely spring supported on the steel structure. However a system like that is very sensible to transfer of vibrations in the floor system from one apartment to another, causing discomfort. In general it can be stated that solutions to increase the acoustic isolation (above 20-30 Hz) increase the transfer of felt vibrations (below 10 Hz).

The applied target value for the vibration level in an apartment caused by walking persons in the neighboring apartment was 0,1 mm/s, single step, root mean square, 90 % value (see Figure 7).

Modelling, Testing and Calibrating of Floor Vibration Behavior. The calculation or prediction of vibration levels in complex floor systems

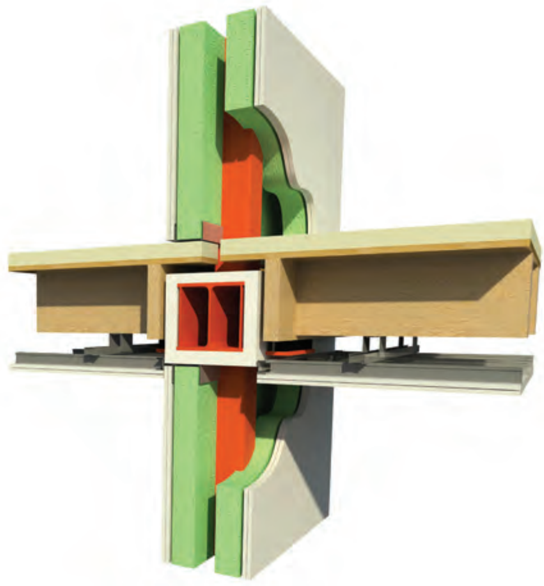

Figure 6. Detail of separated floors and walls (Source: Royal HaskoningDHV)
图 6. 楼板和墙分离的细部(来源于 Royal HaskoningDHV)

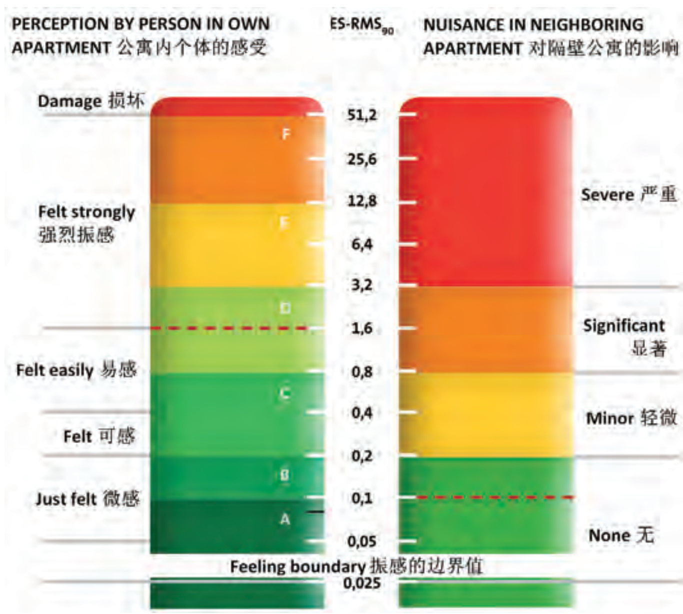

Figure 7. Target values mm/s for vibration level in floor system (Source: Royal HaskoningDHV)
图 7. 楼板系统振动水平的设计值 mm/s (来源于 Royal HaskoningDHV)

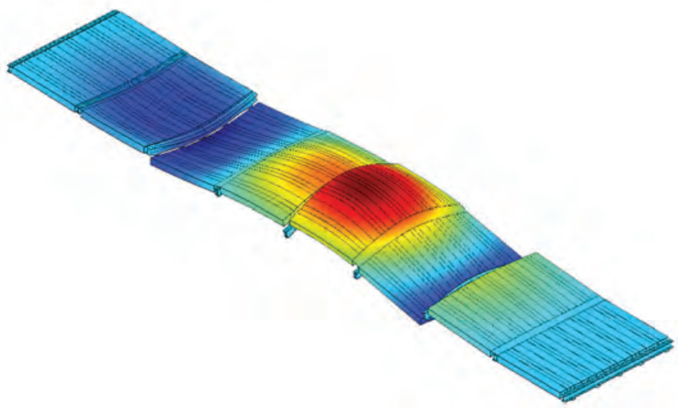

Figure 8. Dynamic FEM model (Source: TNO)
图 8. 动力有限元模型(来源于 TNO)

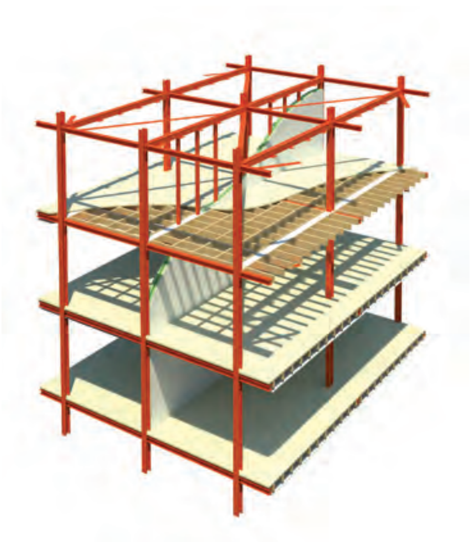

Figure 9. Segment of ultra-light weight building concept (Source: Royal HaskoningDHV)
图 9. 公寓超轻结构的部分示意图 (来源于 Royal HaskoningDHV)

Figure 10. De Karel Doorman in Rotterdam, rendering including structural system (Source: Royal HaskoningDHV)
图 10. 鹿特丹的卡勒尔•多尔曼大厦 (来源于 Royal HaskoningDHV)

depends strongly on specific values which are difficult to predict with the desired precision. For that reason a combination of dynamic FEM calculations with real scale testing was used.

First a dynamic FEM model (see Figure 8) was made containing the structural and floor system and the walls between the apartments. On site a set of test apartments was built in which the transfer of vibrations was measured in detail. A large number of sensors were placed on the sending floor and on the receiving floor, following the path of the transfer of vibrations. In this way the vibration transfer of every step in the system could be analyzed: vertical and horizontal displacements were measured and torsional behavior could be analyzed.

Calibration of the Basic Model. But even more important, with these data the FEM element could be calibrated: the values for stiffness and damping were adapted. In that way a FEM model was obtained with a dynamic behavior similar to the real behavior of the applied materials, dimensions and detailing. In this model it was possible to apply and evaluate design options with the necessary accuracy.

Design Adaptations to Influence the Floor Vibration Transfer. The most important design measures to reach the target value for the vibration level was using a bidirectional beam system in the wooden floors, eliminating acoustic spring rubbers in the mid-beams in the apartments and applying (non-structural) slender steel columns between the steel beams, inside the separating walls between the apartments (see Figure 9). In that way the steel beams react very stiff to vibrations. They reflect the vibration energy, preventing it to pass through to the neighboring apartment. After thoroughly calculating these measures in the FEM model and analyzing the subsequent vibration levels, the final structural and floors system was tested in the test-apartments on site. The vibration levels measured in this last test confirmed the calculated measures which met the target value, thus obtaining a comfortable apartment block (see Figure 10 and 11).

Figure 11. De Karel Doorman in Rotterdam, picture (Source: Ossip van Duijvenbode)
图 11. 卡勒尔•多尔曼大厦 (来源于 Ossip van Duijvenbode)

首先，动力有限元模型 (见图8) 包含了该建筑的结构，楼板和隔墙。通过现场测试，得到了公寓的实际振动性能。在发送地面和接收地面布置了大量的传感器，来测量振动的传播。这样，每一步的震动都可以分析到，横向和水平的位移也将被测出。

基本模型校正: 然而更重要的是，通过这些数据，有限元模型的单元能够被校正: 即刚度和阻尼值可以随之调整。通过这种方式获得的FEM模型，在材料应用，维数和细节方面都具有与实际特性类似的动力学特性。这一模型提供的必要精度，使得其应用和评估设计选择成为可能。

楼板振动的变通设计: 为实现隔震目标，最重要的是在木质楼板内使用双向梁系统，评估橡胶弹簧在梁中部的隔声性能以及在公寓单元之间隔墙内的钢梁间加设非结构细长钢柱 (见图9) 。这样的话，钢梁的刚度会变得很大，从而减小振动。这些构造可以反射振动的能量，从而阻止其传至隔壁房间。在有限元模型中计算这些构造措施并分析相应的振动水平后，对最终的结构和楼板系统进行了现场测试。最后测试结果显示振动水平满足目标要求，从而实现了公寓楼设计的舒适性 (见图10,11) 。

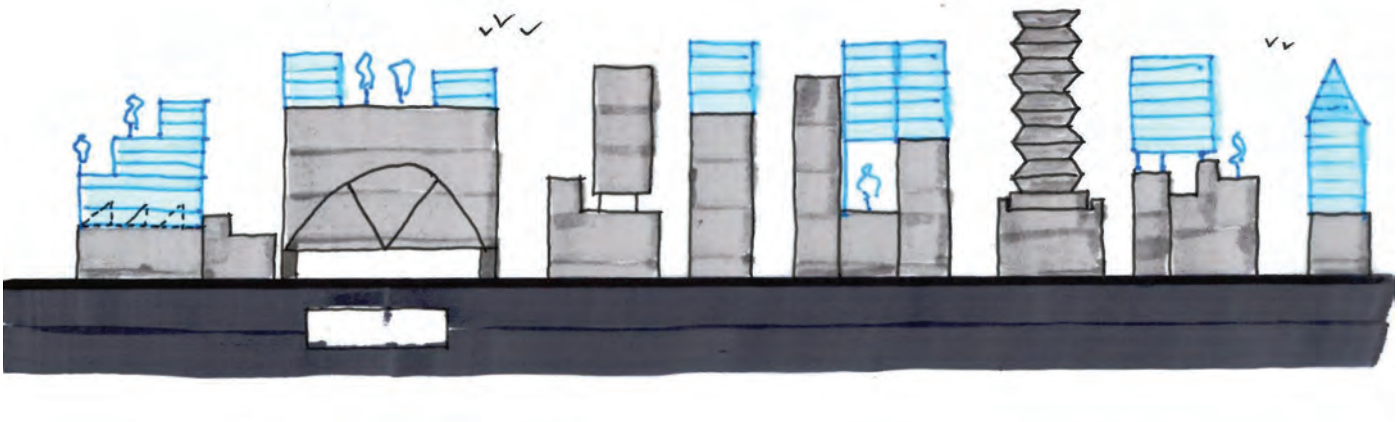

Figure 12. Urban densification future possibilities (Source: Royal HaskoningDHV)
图 12: 城市集约化的未来可能性 (来源于 Royal HaskoningDHV)

Conclusions and Look Forward

The concept of "De Karel Doorman" provides possibilities for urban densification by building on top of existing buildings or infrastructure. There are also great possibilities in floating buildings. The ultra-light weight building system can be adopted with the same approach of FEM calculations with real scale testing and calibrating, for different situations, ensuring a high quality and comfort in terms of acoustic and vibration isolation. This together with smart use and releasing or creating hidden load bearing capacities of existing structures gives great possibilities to add significant amount of apartments or other functions in city centers (see Figure 12). This is done with absolute minimum material use and minimum nuisance for the surroundings and reduction of pollution.

The real value of this concept of urban densification is the enhancement of social safety in existing city centers. But the light weight system and specific materials make the concept also applicable for developing countries.

结论与展望:

"卡勒尔•多尔曼"大厦的理念为在原有建筑上加盖新建筑的城市集约化方法提供了更多的可能性。在漂浮建筑上，这种设计也有着很好的前景。超轻量化建筑体系同样可以用于实际尺寸的有限元分析和校对。它可以保证在各种情况下声学和隔震的舒适性。这种巧妙的运用和释放隐藏承载力的方法为在市中心地区加盖公寓或其它功能的建筑提供了无限的可能 (见图12)，而且它只需要很少的材料，对周边环境影响很小。

这个城市集约化概念的真正价值在于增进城市中心区的社会安全。而轻质系统和特定材料也使得这个概念也可以在发展中国家有广泛的前景。