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Ultra Light Weight Solutions for Sustainable Urban Densification

Maurice Hermens, Michiel Visscher, John Kraus
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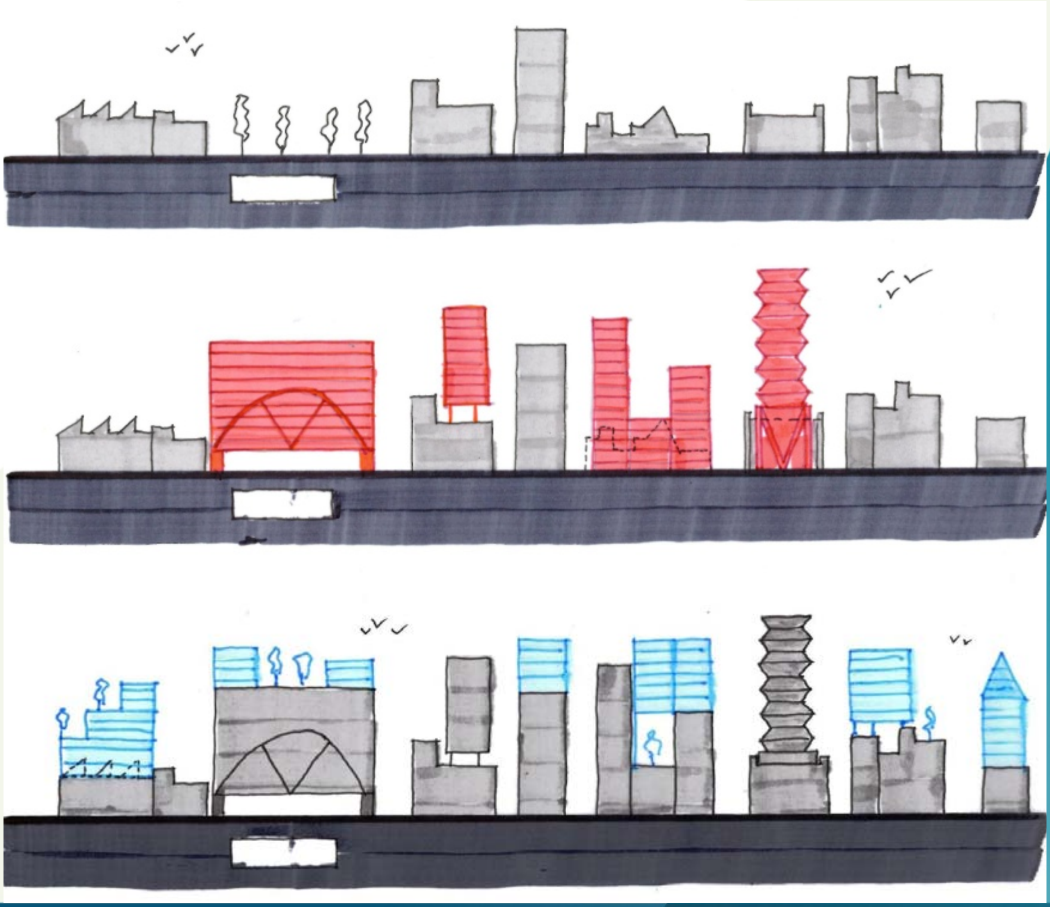

ABSTRACT

This paper[1] 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 centres 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

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[1] *This paper was presented by Maurice Hermens on September 16th on the CTBUH 2014 Shanghai Conference ‘FUTURE CITIES - Towards Sustainable Vertical Urbanism.’*

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 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).

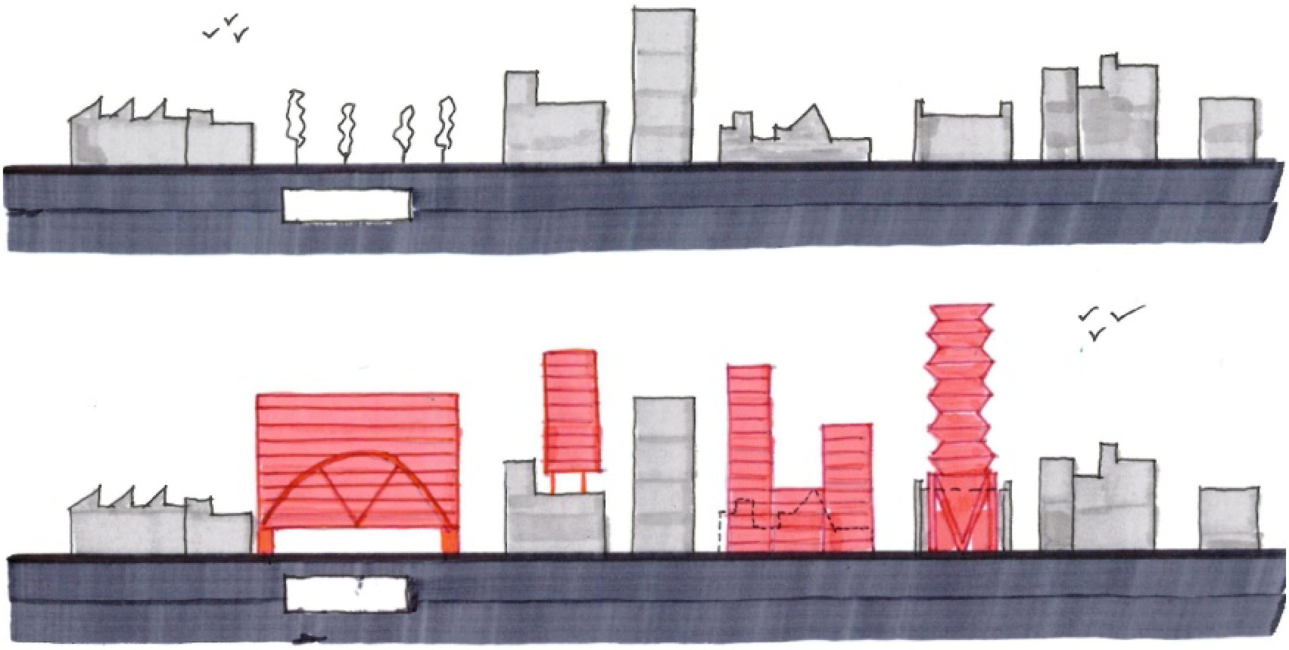

Figure 1. Urban densification concepts (Source: Royal HaskoningDHV)

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 trough 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 facade (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.

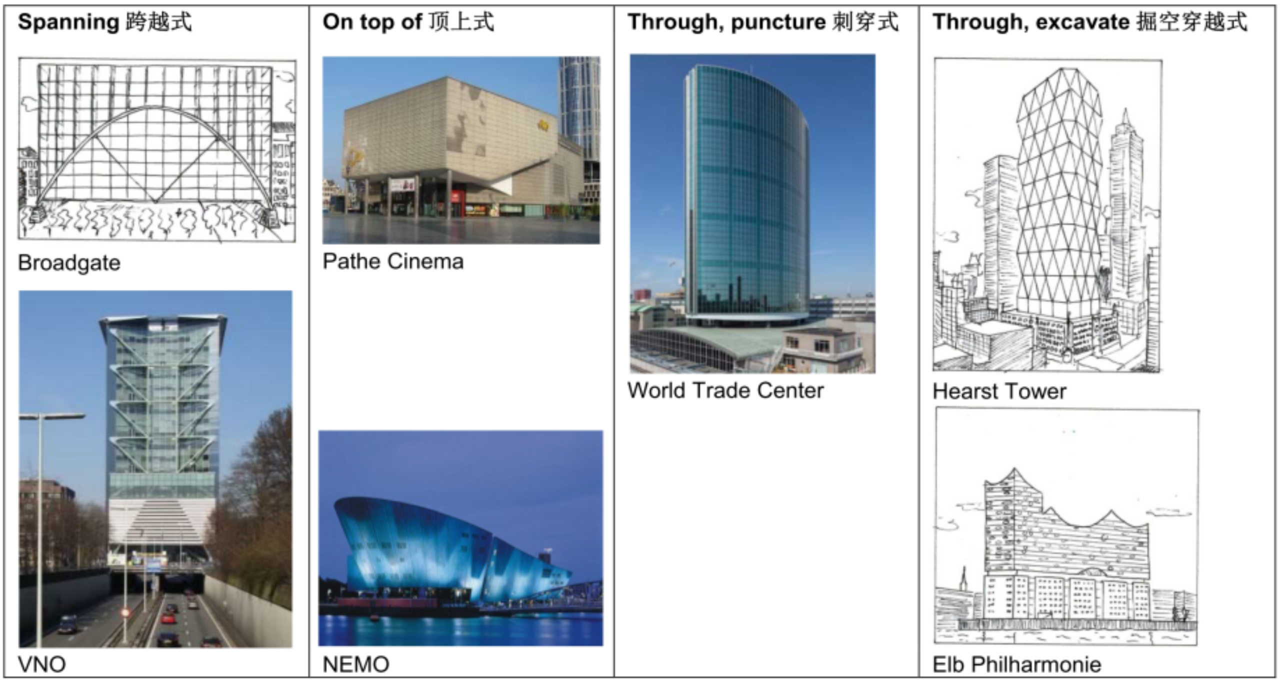

Figure 2. Urban densification examples (Source: Royal HaskoningDHV)

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.

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.

REALISED 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.

Figure 3. The original building ‘Ter Meulen’ (Source: Royal HaskoningDHV)

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.

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.

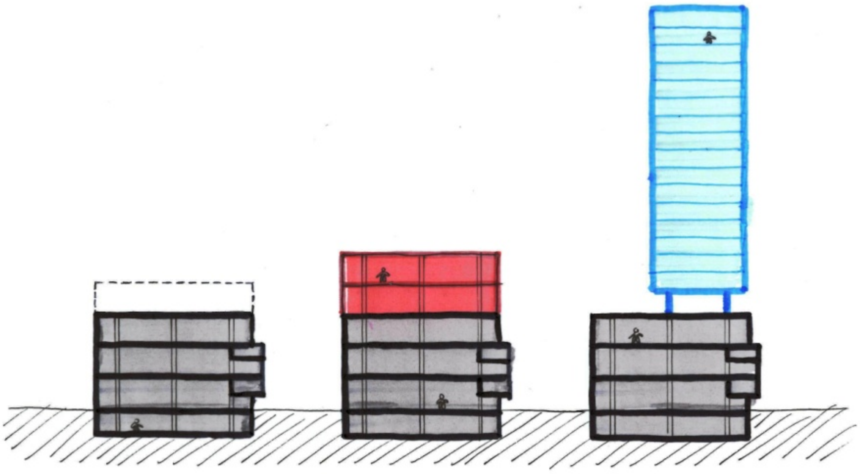

Figure 4. Development of building Ter Meulen (Source: Royal HaskoningDHV)

Solution

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

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

The analyses 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 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).

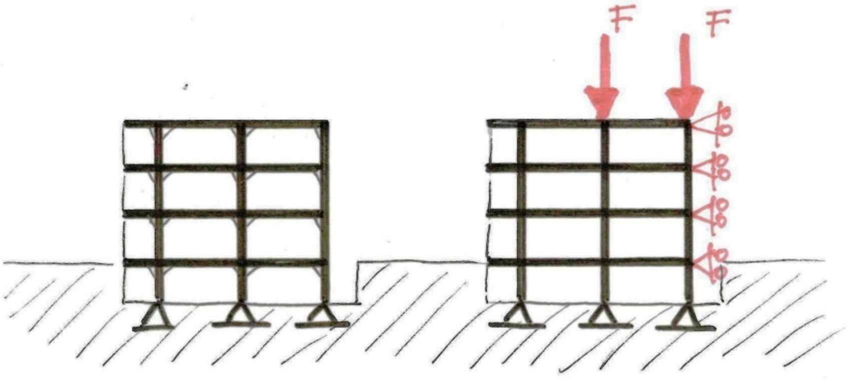

Figure 5. Structural stability scheme before and after (Source: Royal HaskoningDHV)

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 floors within those extra 5.000 kN. The pile groups 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 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-analyses. 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/m^2. 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

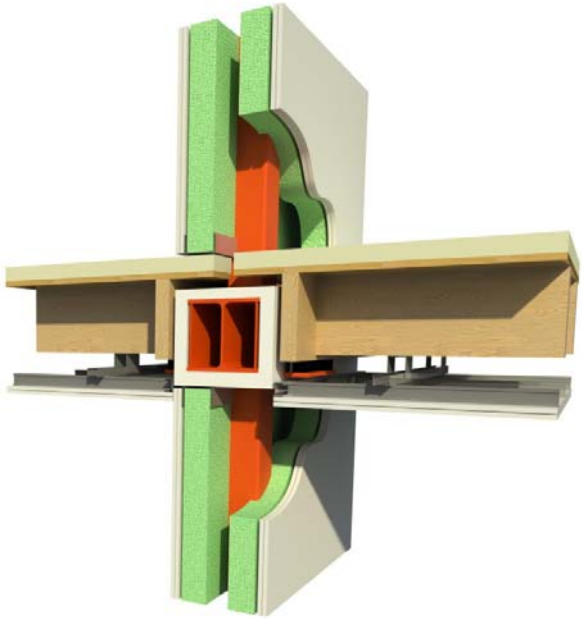

Figure 6. Detail of separated floors and walls (Source: Royal HaskoningDHV)

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).

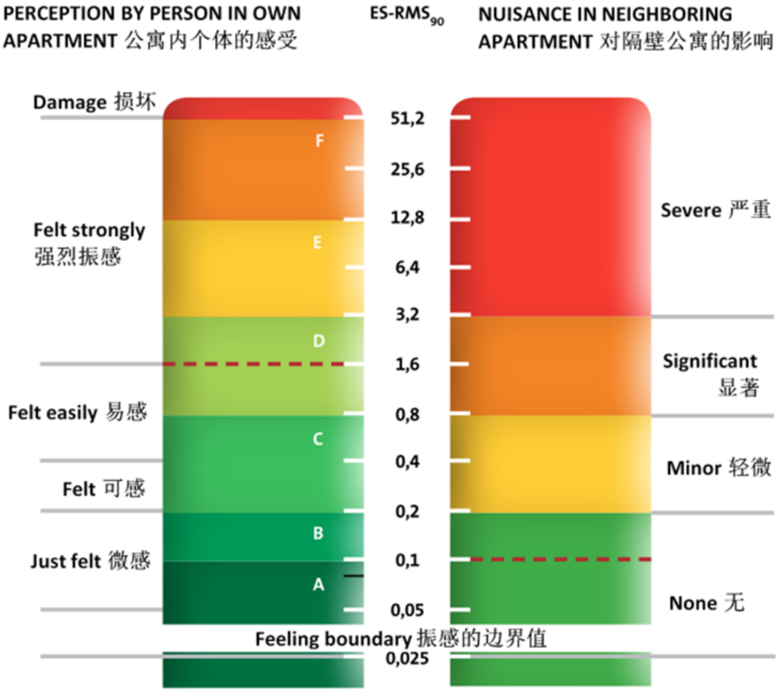

Figure 7. Target values mm/s for vibration level in floor system (Source: Royal HaskoningDHV)

Modelling, testing and calibrating of floor vibration behavior. The calculation or prediction of vibration levels in complex floor systems 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.

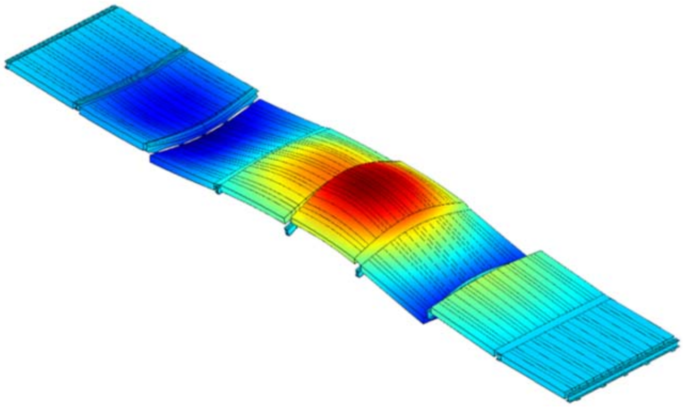

Figure 8. Dynamic FEM model (Source: TNO)

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).

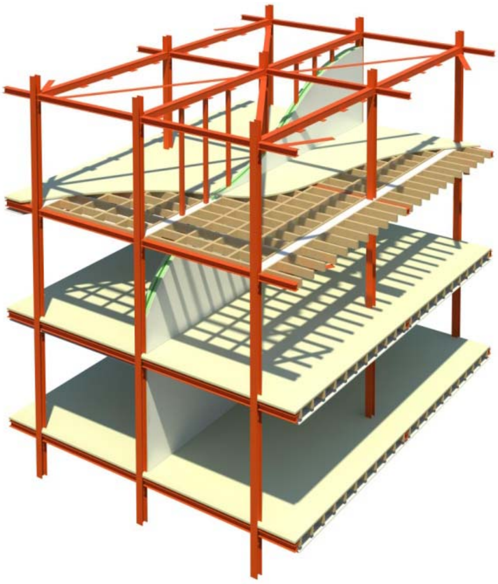

Figure 9. Segment of ultra-light weight building concept (Source: Royal HaskoningDHV)

Figure 10. De Karel Doorman in Rotterdam, rendering including structural system (Source: Royal HaskoningDHV)

Figure 11. De Karel Doorman in Rotterdam, picture (Source: Ossip van Duijvenbode)

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.

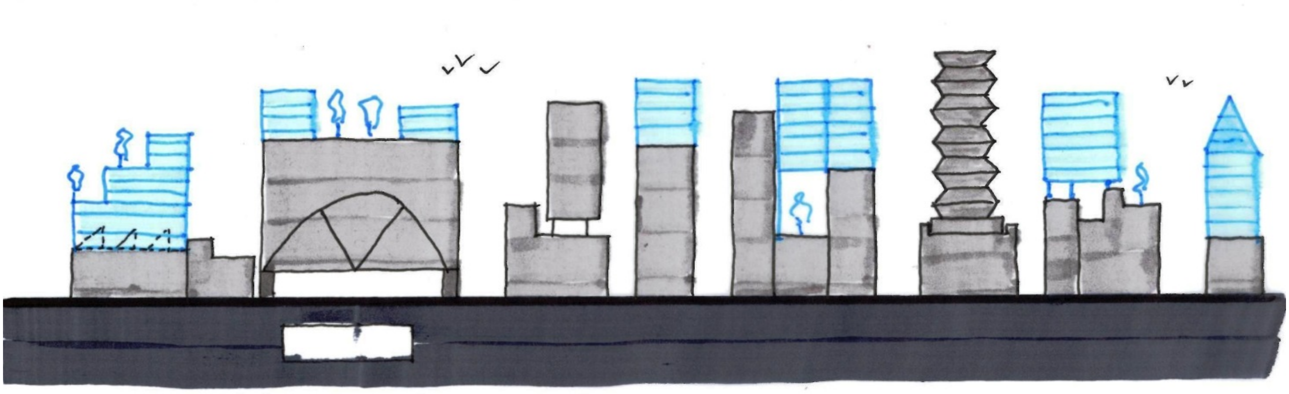

Figure 12. Urban densification future possibilities (Source: Royal HaskoningDHV)

Author: Maurice Hermens

Affiliation: Royal HaskoningDHV
Street Address: George Hintzenweg 85
City: Rotterdam
Zip/Postal Code: 3068 AX
Country: The Netherlands
Email Address: maurice.hermens@rhdhv.com
Fax: +31 10 443 36 88
Telephone: +31 88 348 84 15
Website: www.rhdhv.com

Maurice Hermens. Maurice is involved in many different projects. One common factor in all projects is the great complexity and uniqueness. He is working in both the Netherlands and abroad. Many of his projects are located in dense urban surroundings, underground and above ground. Striking examples are the Market Hall in central Rotterdam. 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.

Author: Michiel Visscher

Affiliation: Royal HaskoningDHV
Street Address: George Hintzenweg 85
City: Rotterdam
Zip/Postal Code: 3068 AX
Country: The Netherlands
Email Address: michiel.visscher@rhdhv.com
Fax: +31 10 443 43 46
Telephone: +31 88 348 84 88
Website: www.rhdhv.com

Michiel Visscher. Michiel 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. Key projects in high-rise are: ‘Vietcombank’ Vietnam, ‘Zohra Tower’ Abu Dhabi, The ‘Karel Doorman’ Rotterdam, ATC tower in Ashgabat, Turkmenistan, Hotel above Eindhoven Airport, Renovation railway station the Hague.

Author: John Kraus

Affiliation: Royal HaskoningDHV
Street Address: George Hintzenweg 85
City: Rotterdam
Zip/Postal Code: 3068 AX
Country: The Netherlands
Email Address: john.kraus@rhdhv.com
Fax: +31 10 443 36 88
Telephone: +31 88 348 84 88
Website: www.rhdhv.com

John Kraus. John Kraus started as structural engineer and became a leader of professionals. He designed many icon buildings, among which high rise buildings with foundations on soft soil (New Orleans building and the Millennium Tower, both in Rotterdam) and the first outrigger in the Netherlands (Fortis Bank tower). In 1985 he became co-owner of an engineering firm of about 200 people. In 1998 this firm became part of DHV, which in a merger in 2012 became Royal HaskoningDHV. After 5 years of success he was appointed in 2009 as leading professional.

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