▲ FIGURE 1: MUSEUM ARNHEM ©JANNES LINDERS

Museum Arnhem: structural design

WRITTEN BY IR. C.F. BOSVELD, BOUWEN MET STAAL

The extension of the Museum Arnhem looks spectacular because of the new wing that cantilevers above a moraine. For the museum, the internal routing and flexible layout are of great importance. For instance, a supporting structure was designed with load-bearing trusses in the facades, eliminating the need for intermediate columns and allowing for the creation of the large cantilever on the Rhine side. The structure is concealed and unobtrusive, subordinated to the overall experience and architecture. However, the symbolic effect of the desired image makes the structure even more important.

In 2016, a design team was put together with Benthem Crouwel Architects, DGMR, Nelissen ingenieursbureau and Pieters Bouwtechniek. The extension for the museum was designed with this team. Pieters Bouwtechniek was responsible for the structural design and its development, including the tender process. In the implementation phase, the plan was further elaborated by contractor Rots Bouw with coordinating structural engineer ABT. Pieters played the role of design engineer in the implementation phase.

The oldest section of the existing museum, constructed in 1873 and originally designed as a gentlemen's club by Cornelis Outshoorn, comprises a central hall with a dome and two wings. Originally, the dome was very open and oriented towards the garden. In 1920 it was converted into a museum. To accommodate the exhibition of the art collection, the facades facing the garden and the void in the dome were closed. The western wing, designed by Frits Eschauzier, was added in 1956. In 2000, a temporary wing on the east side, by Hubert-Jan Henket, which housed the museum café, was added.

Design

The design team developed an extension for the museum that preserves the existing monument and reopens the dome. The wings added in 1956 and 2000 have been removed. The new museum rooms have been situated at ground level to provide clear views of the surrounding landscape from various areas within the building. Under these rooms, in the moraine, there is room for supporting functions for the museum.

In the first design, a single-storey basement was present under the new building. The new building had a cantilever of ± 21.6m on the Utrechtseweg side, and a cantilever of approximately 24.3m on the Rhine side. It became clear during the first explorations of the structural design that the large cantilevers had to be made with steel trusses. This is the most efficient structure. With this as a starting point, variant studies have been carried out in which the influence of different floor systems has been investigated. The required construction heights, maximum floor span and thus maximum centre-to-centre size of the load-bearing trusses and the total weight of the steel structure were considered, as this is an important indicator for the construction costs. Ultimately, the most cost-effective solution involved utilizing concrete hollow core slab floors that spanned directly between the two trusses. This design was further developed.

Cellar

Already in the preliminary design an extra basement layer was added. This is where the museum's depot will be located. By locating the depot in the moraine, a sustainable and energy-efficient climate concept can be developed. Due to the constant temperature of the surrounding soil and adjacent spaces, the desired temperature in the space can be achieved with as little use of installations as possible. Thermal mass helps dampen external influences. The climate concept for the depot is characterized by a massive structure and such thermal insulation that there is a heat balance in which the depot cools down slowly. This involves active heating and active dehumidification. To achieve the required thermal mass, the cellar floor is made of 35cm concrete and the cellar walls of 40cm concrete. The intermediate floors are made of 320mm thick hollow core slab with a compression layer. The thickness of the concrete structure helps prevent water ingress. For extra security, however, all floors and walls adjacent to the bottom are provided with a water barrier between concrete and insulation on the outside.

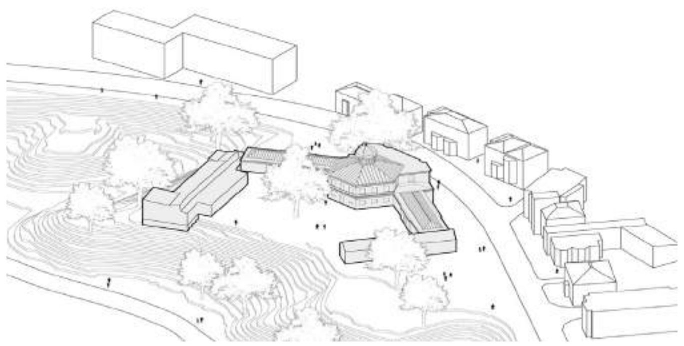
Flooring

The considerations from the variant studies, together with the wishes of the museum and the architect, have led to a structural design in which the volume has become slightly narrower than in the first studies. As a result, the facade surface decreased and the structure could be placed in a logical place for the museum route. The new volume has also been rotated slightly in relation to the existing building, so that the new wing ended up more favorably on the moraine.

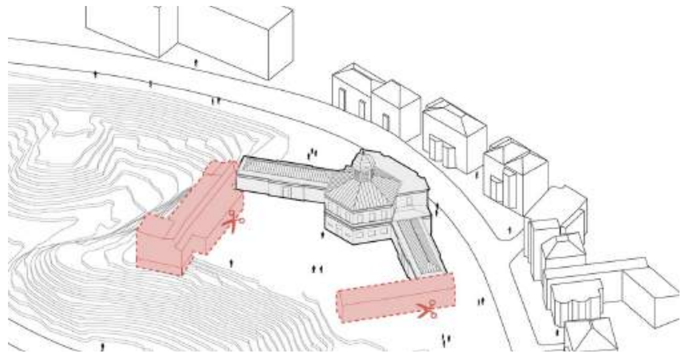
The floor span of the -1 floor is divided into two sections of 8.4m each and made of a 320mm thick hollow core slab with a compression layer. Supported on the central axis by steel beams on columns.

In the first basement layer on the Utrechtseweg side, installation rooms, shipping and support functions are present. Here it was possible to continue the load-bearing line in the middle of the building. This allows the floor of the exhibition space to span 2x8.4m. This floor is also designed as a hollow core slab floor, also 320mm thick with a compression layer. A column-free exhibition space was desired on the Utrechtseweg side. The roof in this area spans the entire 16.8m. The roof is made of 40mm hollow core slab with a compression layer and rests on the trusses in the facades. On the roof, the load from ballasted PV panels and/or a light sedum layer (1 kN/m2) and a variable load of 2 kN/m2 have been taken into account. The exhibition space on the Utrechtseweg side extends as a cantilever approximately 5.4m beyond the cellar wall. The span direction of the floor of the cantilever is rotated so that it spans from the cellar wall to the truss in the end facade. This truss hangs in the trusses in the side walls.

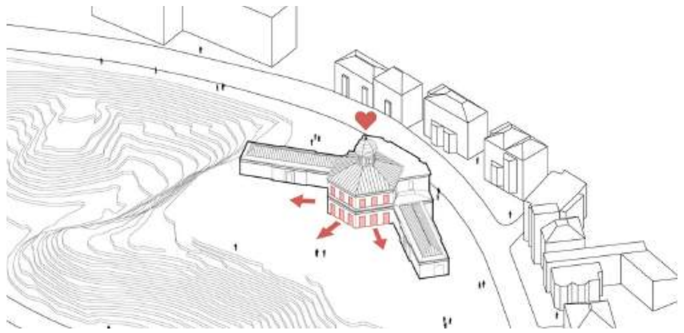
On the Rhine side, a column-free space is also desirable in the first basement layer because of the divisibility of the office space. Structurally, it was also useful to design the ground floor without an intermediate support point.



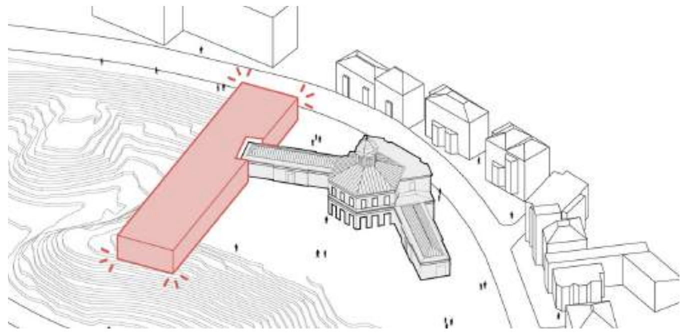
▲ FIGURE 2: EXISTING MUSEUM ON THE EDGE OF THE MORAINE WITH TWO LATER ADDED WINGS © BENTHEM CROUWEL ARCHITECTS



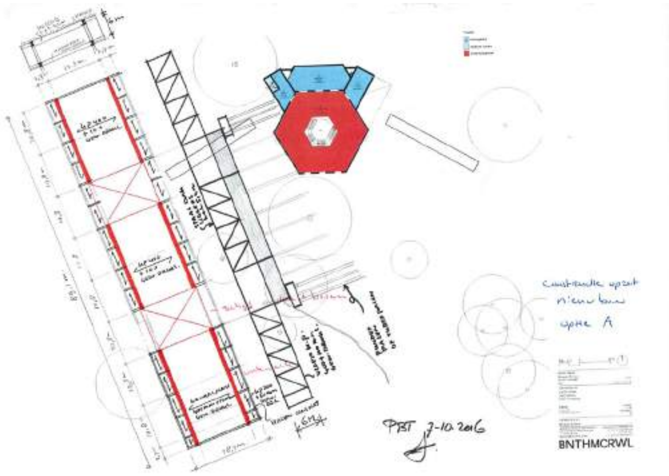
▲ FIGURE 3: ARCHITECTURAL DESIGN © BENTHEM CROUWEL ARCHITECTS



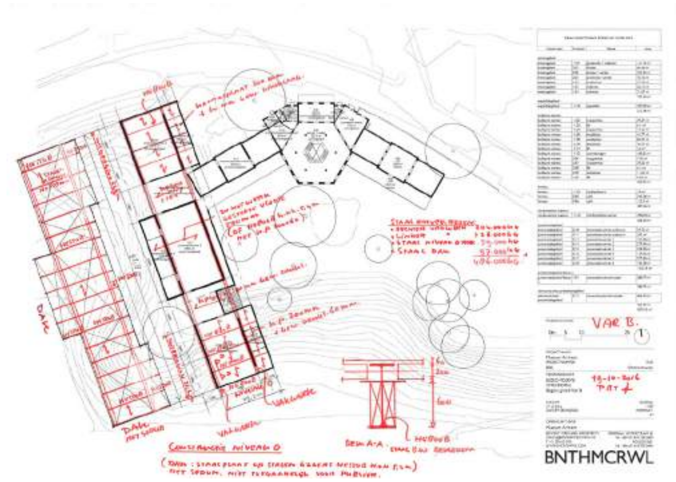
▲ FIGURE 4: ARCHITECTURAL DESIGN © BENTHEM CROUWEL ARCHITECTS



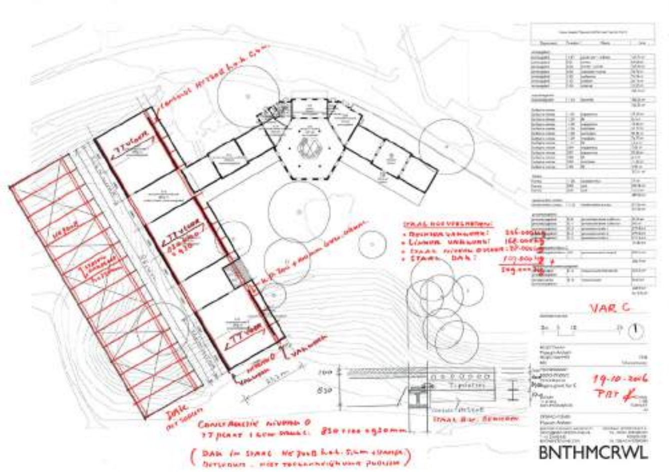
▲ FIGURE 5: ARCHITECTURAL DESIGN © BENTHEM CROUWEL ARCHITECTS



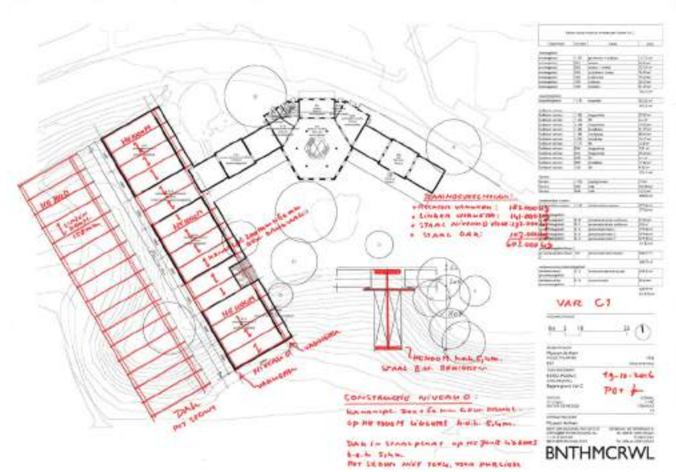
▲ FIGURE 6: VARIANTS STUDY



▲ FIGURE 7: VARIANTS STUDY



▲ FIGURE 8: VARIANTS STUDY



▲ FIGURE 9: VARIANTS STUDY

As a result, the floor rests completely on the trusses and the weight of the floor acts as a counterweight for the cantilevers. The load-bearing trusses are positioned on axis 1 and 3 in this area, in the sidewall on the west side of the building and in the dividing wall between the exhibition space and the corridor on the garden side. As a result, the floors span ± 14m. With a desired variable load of 7 kN/m2 and the necessary structural and technical installation conditions, this was practically the maximum possible span for the 400mm hollow core slab with compression layer. The roof here is identical to a 400mm hollow core slab with compression layer. The exhibition space in the cantilever is the so-called daylight room. A lighter steel/glass roof has been used here. Both the floor of the exhibition spaces and the roof rest on the large trusses.

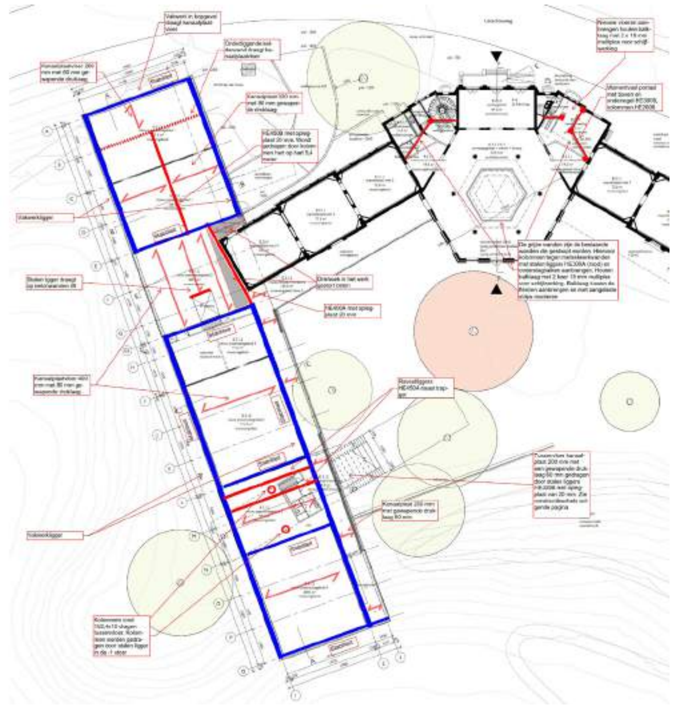
Half-timbered

Because the existing building protrudes into the volume of the new building, and a large window is located on the west side at this position, a truss with a small cantilever of approximately 5.4m is formed on the Utrechtseweg side and a truss with a large cantilever of approximately ± 16.2m on the Rhine side. In a later round of cuts, the cantilever there was reduced to 14.4m. Directly behind the large cantilever, the publicly accessible balcony protrudes through the building volume.

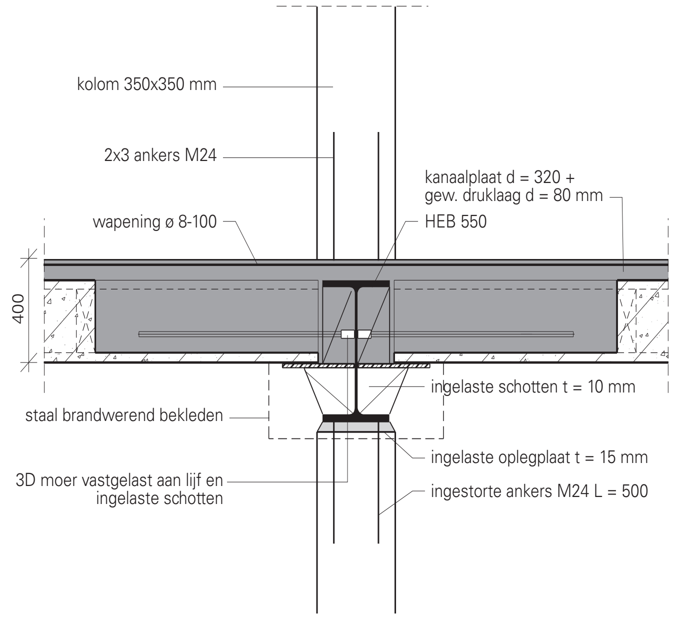
During the Definitive Design stage, it was discovered that the new building would be too expensive. The design team looked for possible cost savings. Options were examined to make the cantilever smaller, but to keep the daylight room the same. A shortening of 1.8m, 2.7m (half grid) and 5.4m (full grid) was considered. This saves facade surface and reduces costs on the steel structure. The shortening therefore reduces the passage for the public balcony. Finally, a reduction of 1.8m was implemented. As the basement was not reduced in size, this creates a somewhat unusual structural arrangement in which the stability wall, which separates the daylight room from the balcony, is no longer above the basement wall.

As a result, an extra diagonal and column are required in the main trusses to absorb this force. The stability forces are dragged through the compression layer. An additional advantage is that the span of the bottom and top chord at the passage of the balcony has been reduced. The HD beams used have a favorable cross-section for absorbing normal forces, but they are somewhat less favorable at high bending moments.

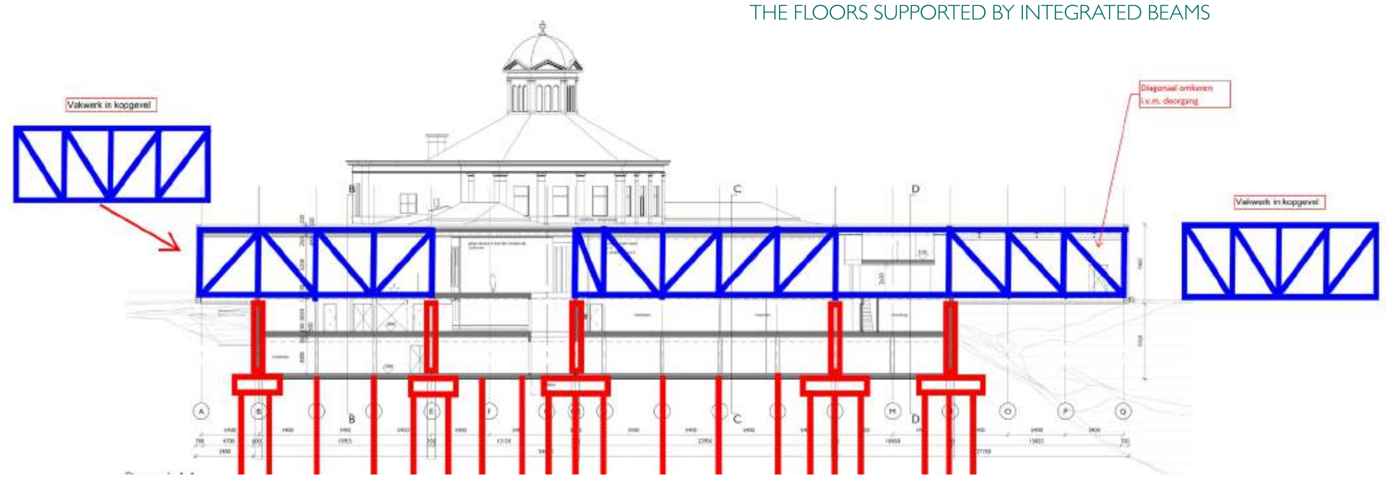
The exhibition spaces are located on the ground floor. The layout here is completely determined by the museum route. The layout of the exhibition spaces is visible in the layout of the main trusses. The partition walls between these spaces provide the transverse stability of the superstructure. The roof floor and the ground floor are designed as a disc through which the forces from the stability elements in the superstructure are transferred to the stability walls in the substructure. The floor and the roof are supported by the bottom and top chord of the trusses.



▲ FIGURE 10: STRUCTURAL DESIGN



▲ FIGURE 11: DETAIL OF CROSS-SECTION ON CENTRAL AXIS WITH THE FLOORS SUPPORTED BY INTEGRATED BEAMS



▲ FIGURE 12: TRUSSES PRINCIPLE

On the garden side, the load-bearing truss is 2.7m within the volume. The ground floor spans here between the bottom chord of the truss and the cellar wall on axis 4 and is designed as a 200mm hollow core slab with a compression layer. At the cantilever, this floor is supported by girders that cantilever perpendicular to the trusses. This has been solved with moment-resistant knots in the steel and extra reinforcement in the compression layers.

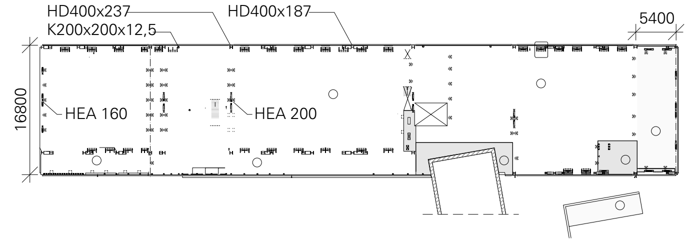
Different sizes of HD beams are used in the bottom and top chords of the trusses. With these beams, the inside dimensions between the flanges are the same. When connecting the various beams in line with each other, the center of gravity of the beams must be at the same height. This varies the outside dimensions of the bottom and top chord of the trusses. The floor support is made with a plate on the bottom flange of the beam so that it is always at the same height.

The climate installations in the museum require a lot of recesses through the floors close to the supports. Already in the design process these recesses have been matched to the width of the hollowcore slabs. The recesses directly at the support of the hollowcore slabs were not possible with a standard trimmer joist. For this purpose, steel 'shoes' have been connected to the bottom chord of the truss. On this shoe the hollow core slab is placed. The resulting eccentricity is supported with reinforcement bars.

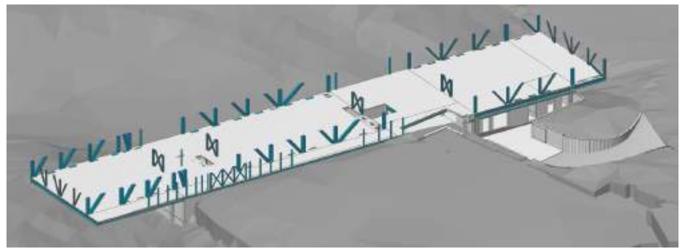
Mezzanine floor

Directly behind the large cantilever, an intermediate floor protrudes through the volume. This floor is a publicly accessible balcony from the museum garden with a view over the Rhine and the floodplains. The free height above and below the balcony determines the height of the entire volume. As a result, the structure is as slim as possible and integrated into the floor thickness as much as possible. The structure rests on the main truss on axis 1, in the middle on columns that protrude through the ground floor to the steel girder in the -1 floor and on the basement wall on axis 4, on the side of the museum garden.

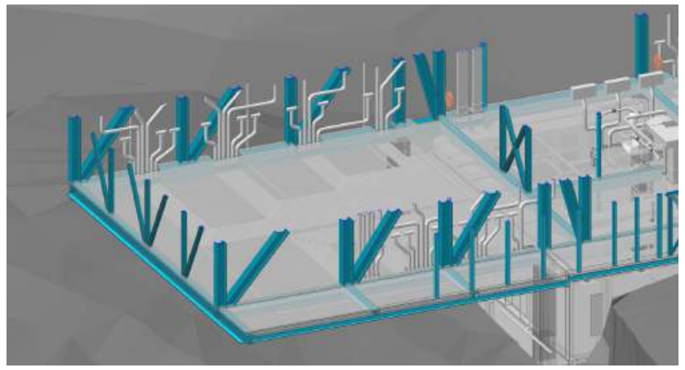
At this location, directly behind the cantilever, the bottom and top chord of the main trusses are subjected to maximum tension and compression. In addition, the bottom and top chord at this location create the largest span between the verticals and diagonals of the truss, so that they are also subjected to bending by the load from the floors.



▲ FIGURE 13: STRUCTURE ON THE GROUND FLOOR



▲ FIGURE 14: STRUCTURE ON THE GROUND FLOOR



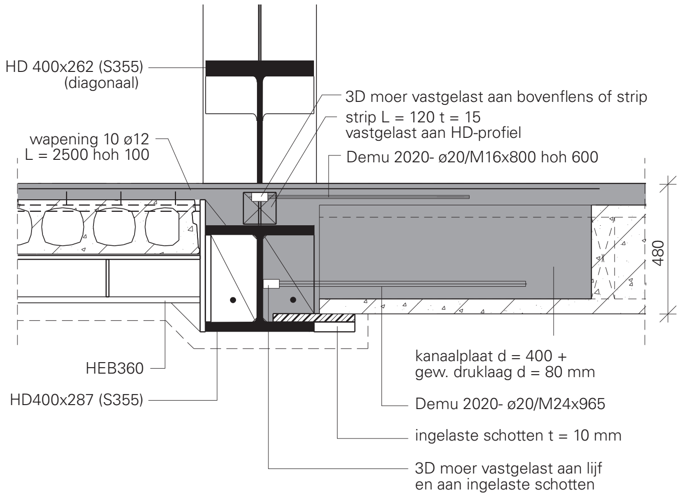
▲ FIGURE 15: INSTALLATION RECESSES IN FLOOR

As a result, a HD profile is required at this location and this location is indicative of the height of the new wing.
The transverse walls provide the transverse stability of the superstructure. The space for bracing is limited due to the walls' thickness and the presence of sliding doors. In the available space, a structure with bracing has been designed that provides stability and that also transfers its loads to the main trusses at locations where there is no wall under the structure.

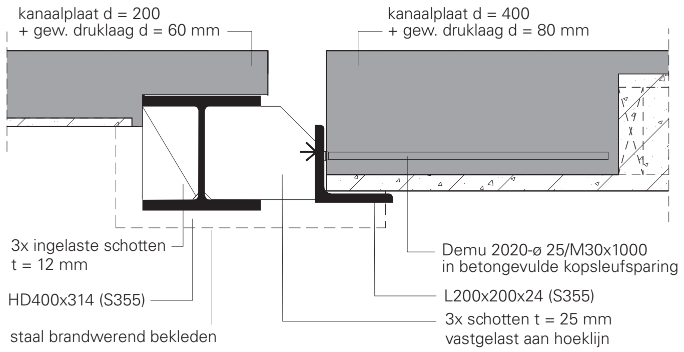
The trusses on axis 1 and 3 are similar. The truss on axis 3 is somewhat heavier because of the greater floor load that is exerted on it. On axis 1, the top chord of the truss on the Rhine side continues to the truss on the Utrechtseweg side. It is very important to keep an eye on the construction sequence for the final force effect in these trusses. This also applies to the choice of fixed and sliding supports. The nodes of the trusses are welded entirely to ensure robustness and for an alternate load path. The construction elements are connected at the points where the bending moment is zero.

Performance

In the Design Specification Pieters looked at the possibilities for the execution and assembly of the large trusses. The initial approach was to weld the truss nodes in the factory as much as possible and that the trusses would be assembled out of as large elements as possible. This is to minimize the number of bolt connections that were to be applied at higher altitude. An important starting point for the tender was that the embankment under the trusses will be excavated



▲ FIGURE 16: DETAIL FLOOR SUPPORT ON THE HD PROFILE AND CANTILEVER PERPENDICULAR TO TRUSS



▲ FIGURE 17: DETAILED INSTALLATION OPENING WHEN HOLLOW-CORE SLAB IS LAID

to the level of the -2 cellar floor during installation, and that further adjustments are not desirable. A heavy crane could be positioned at the base of the slope. The design team was very aware of the difficulty of this erection sequence. The tenderers were therefore explicitly asked to include this aspect in the tender. Contractor Rots Bouw, together with CT de Boer and ABT, has worked out a plan in which the steel structure, including the floors, is built above the basement. After placing the floors, compression layers and part of the facade, the steel structure was extended over a sliding track. The steel structure is supported as much as possible at the places where the final supports are located, so that the structural scheme does not change and deformations remain under control. Because of the existing building, which is partly in the volume of the new building, the trusses had to be constructed and extended in stages. The steel supplier Rijnstaal has further elaborated the trusses, divisions and details. In the metalworking workplace of Rijnstaal, the trusses are pre-assembled to check the fit.

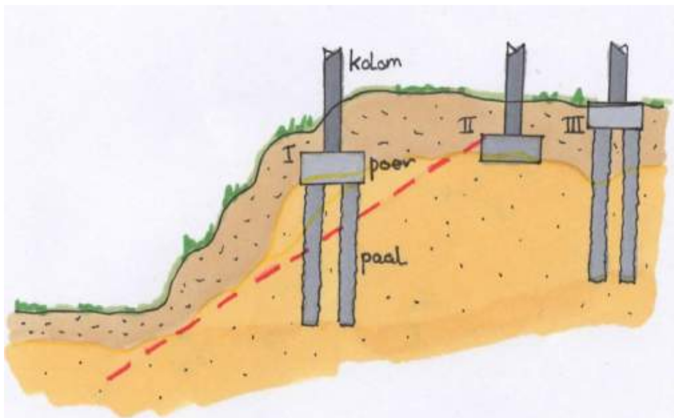
Foundation and construction site

The subsoil in the moraine is very hard and gravelly. In principle, this surface is very suitable for a shallow foundation. Due to its location on the edge of the moraine and the large concentrated loads from the superstructure, it was not possible to have a shallow foundation along the edge of the moraine. In the Design Specification it was decided to place the entire new building on Fundex grout injection piles. This makes the structural design unambiguous and simple. However, on the cramped construction site with height differences between the existing museum and the moraine, working with a heavy drilling rig is a challenge, for which a proposal was included in the Specification.

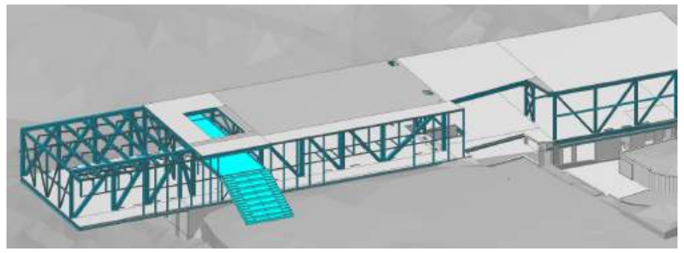
▲ FIGURE 18: DETAILED INSTALLATION OPENING WHEN HOLLOW-CORE SLAB IS LAID

In the implementation phase, contractor Rots Bouw, together with the coordinating structural engineer ABT – who had already carried out an exploratory study into the possibilities of underground construction at this location in the preliminary phase – worked out the foundation as a pile-plate foundation. With this solution the good load-bearing capacity of the subsoil is used. Only at the edge of the moraine and under the large concentrated loads from the superstructure foundation piles are applied to prevent the soil mass from sliding away.

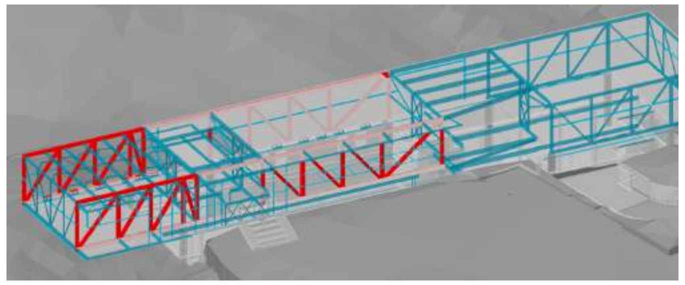
The new basement is one layer deeper than the basement under the existing west wing of the museum. The existing museum is founded on a shallow foundation. In the design phase it was devised to inject the ground under the existing building with a water glass injection, to prevent subsidence of the existing building during the construction of the new basement. This makes it possible to excavate practically vertically next to the existing foundations. In the implementation phase, this plan was replaced by a pile wall surrounding the existing wing constructed by the contractor and the coordinating structural engineer. This was only possible in combination with the other changes made to the foundation design, as the original design had large piles positioned close to the existing building that would collide with the pile wall and purlin.



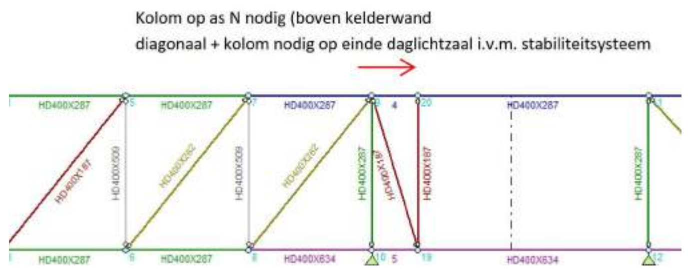
▲ FIGURE 23: FOUNDATION ON PILES AND ON STEEL NEXT TO A STEEP SLOPE - FROM QUICK-SCAN ABT



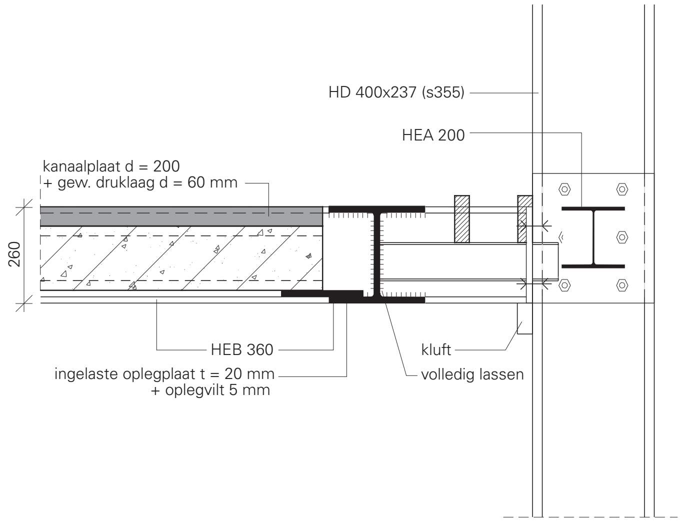
▲ FIGURE 19: CONSTRUCTION MEZZANINE / BALCONY



▲ FIGURE 20: TRUSSES ON AXIS 1 AND 3



▲ FIGURE 21: STRUCTURAL SCHEME WITH CUTBACKS



▲ FIGURE 22: DETAIL OF MEZZANINE FLOOR

▲ FIGURE 24: CONSTRUCTION SITE WITH PILE WALL AROUND THE HEAD OF THE EXISTING WING