N E W

Museum of Danish Resistance

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Abstract

The master thesis by Zofia Zelazny engages with experience design in the context of a historical museum. The project gives a proposal for the New Danish Resistance Museum in the Churchill park in Copenhagen, basing on the restricted competition announced by a.o. the National Museum and the ministry of Culture in 2014.

The project seeks to create a landmark for the city that tells the stories of the fight for freedom during the nazi regime. The experience of the exhibition is staged by an architectural story about the fear and tension of wartimes. The design works with the tectonic approach of uniting constructional and aesthetic principles and creates a massive and monumental expression.

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Introduction

A contemporary historic museum is at the same time a space for experiences, learning and reflection. It is an embodiment of the identity of a given place, understood in wide terms of nation, history and culture. By delivering a strong narrative, past and present become connected, through the exhibition, as well as through the architectural tale.

A modern historical museum is a knowledgebase accessible to the civil public, and therefore plays a role in the general education and self-perception of people in a national context.

A museum is an unit of production of cultural meaning. The museum visit is though not exclusively an intellectual, but also an emotional and aesthetical experience. The sensual impressions and the encounter with the exhibited objects is staged by the architecture.

In April 2013 the museum for Danish WW2 resistance fight burnt down, and this year the a.o. National Museum announced an architectural competition for a new building proposal. The project develops an architectural experience that supports the story of civil courage, moral dilemmas, conflicting responsibilities and the difficult act of taking a decision. The design investigates how to offer the visitors suitable spaces to interact, study, socialize and reflect during their visit.

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Motivation

Second World War stands as a time of crisis and redefinition of the order of the modern world in Europe. It´s a trauma that for us who live today seems far away, but still forms the background of our understanding and identity. I find it giving, always to return and rethink conflicts and dilemmas of the past, to better understand the present. Not only on a sociological and political level, but also at the level of the single life story.

The theme of resistance fight is linked to the human struggles with choices, fear, courage, beliefs, trust and betrayal, more than many other historical themes. The existential questions from back then are still valid today and call for reflection and thoughtfulness.

I find a great enjoyment in museum visits, and see a potential in physically being present in a museum, when the everyday life is more and more dominated by digitalization, dematerialization and an intense flow of superficial information. The museum offers the authenticity of the exhibited objects and a certain mental room as a break in everyday life for reflection.

Here architecture comes into play, by putting focus on the physicality and bodily experience of the exhibition environment. By a pronounced atmosphere and sensuous experience, the architecture can offer some reconnection with the poetic experience of simple observation. That awareness and presence, I believe, makes us feel more rooted in reality. A poetic, architectural experience can add value to a museum visit, that otherwise would be purely intellectual. The project strives to find a poetical war time museum design.

“Both narrative and bodily experience tell us something fundamental about making of the human self.”

Jonathan Hale (2012, p. 199)

Methodology

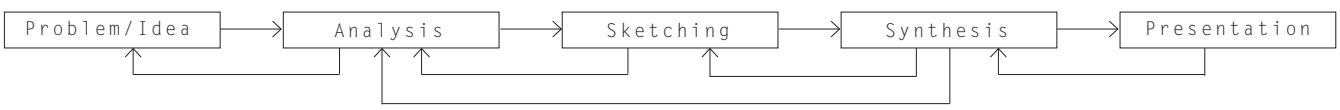
The project springs from Aalborg University's model of problem based learning, where an actual case is the generator for a search for solutions. The project takes departure in the competition brief by a. o. Nationalmuseet (2014), providing information about the exhibition contents and wishes for the new museum. The problem or task for the museum design includes technical, social, cultural questions. It has to consider issues of exhibition strategies, the role of the museum in society, the storytelling and interpretation of the past.

Following the steps described as the integrated design process by M. Knudstup (2014) allows to bring different aspects of the design into play early on, and move from general, loose ideas to more and more specific shapes through iterative investigations.

The analysis phase consisted of contextual analysis of the site, as well as studies of principles of museum architecture. Many visits to museums in Denmark and abroad gave a broad frame of references to compare to and use as fragmental case studies or examples.

The sketching took departure from the placement in the urban surroundings, the wished movement through the museum and functional organization. The structural concept was then further developed through calculations and aesthetic evaluation. The process of architectural design requires a dual attention on the tangible and intangible aspects of the built. With structure as the main technical focus of the project, the architectural vision from the beginning included concepts on build ability and atmosphere generating potentials within the given construction system. Other aspects as energetic efficiency or costs were not taken into account.

Through the whole process the central consideration was on how to use architecture as a storytelling instrument. The theme and content of the museum had high priority, as to express its "inside" on the outside. The interplay between whole and detail encircles gradually a design solution. To finalize the project the synthesis phase required systematization of ideas and prioritizing the design criterions formulated from the analysis. The presentation phase then revealed the projects final form and illustrated its qualities.



Tectonic approach

The term tectonics has been described and interpreted by numerous theoreticians to shed light on the processes in creating and constructing architecture.
A given building's form is influenced by many factors, from banal, practical ones to general, broad contextual issues. As K. Frampton puts it: *" ... we may claim, that the built invariably comes into existence out of the constantly evolving interplay of three converging vectors, the topos, the typos and the tectonic." (Frampton, 1995, cited in Desplazes 2013, p. 10)*

Each of the three factors contains many complex sub themes as illustrated in the diagram. From project to project they will have different relevance and be given different priority. A truly holistic approach is an utopian ideal that should be strived for by involving as many of the factors as possible. The tectonics, are here understood as the way of building, from characteristics of the chosen material to structural concepts and execution. All the physical aspects of the act of building itself are part of the complex world, that the architectural piece must respond to.

In addition to this, comes the artistic vision of the design. Within the innermost circle of the diagram lay still many different approaches. As A. Deplazes states: *"Composition is not an inevitable result. Within the bounds of logical solution there always exist different options."* (Deplazes, 2013, p.10). Those different options leave room for the architectural intention. The poetic space often comes to life when the intention generates the leading concepts for both structure, detailing, materials, as well as the treatment of site and function. The tectonics are then a means to embody the architectural intention, through the physical construct.

The interplay of the tangible and the emotional is well described by M. Hvejsel by the terms of "gesture" and "principle". (Hvejsel, 2011) What the space "does" and "how does it do it" are two sides of the same coin. The gesture being the impact on the user evoking emotion, while the principle describes the architectural means by which the given emotion is achieved. In this way, the atmospheric qualities are linked to the tangible construction concepts. Using this tectonic approach as a tool, the technical and artistic aspects of the design can be considered simultaneously. They can inform and strengthen each other to achieve a coherent expression. The unity of structural principle, details and the poetic narrative has the potential to produce convincing and honest architectural tales.

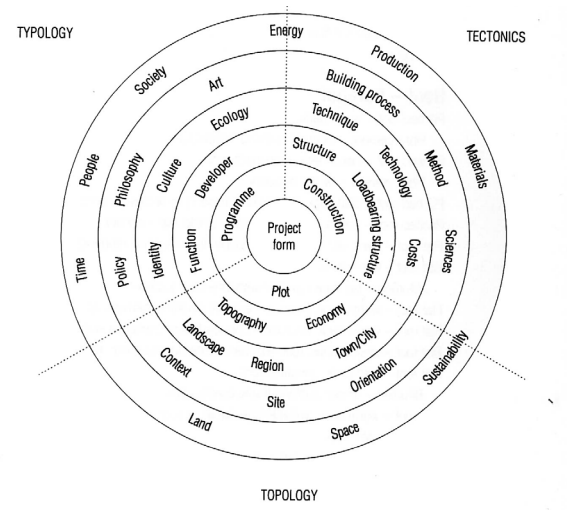


Fig: (Deplazes, 2013, p.10)

Traditional cabinet exhibition, with a strong expression of materiality.
Neues Museum, by David Chipperfield.

Exhibition combined with the architectural element of the stairs.
Moesgaard Museum, by Henning Larsen architects.

Exhibition space dominated by mulimedia.
Moesgaard Museum, by Henning Larsen architects.

Museum architecture

Glass cabinet or theater of the senses

To understand museum architecture, it is crucial to study the very notion of exhibiting. It means to hold out something, to offer it to the audience (Dernie, 2006). The architecture defines the frame in which this encounter between object and observer comes into place.

Museum architecture has in the last century undergone a radical shift in societal role and dissemination methods and media. The first museums of the 17th and 18th century's museum were symbols of status. The objects had to "speak for themselves", displayed as an accumulation of curiosities. With the enlightenment era came ideas about the museum as knowledgebase and its pedagogical role. Classification and organizing of the objects became an important discipline and the building had to provide a structure for that. (Newhouse, 2006)
The typology of the traditional museum is monumental, almost sacral, and there is a certain distance between onlooker and object. It is a social space of exclusivity and a certain behaviour codex is expected. The architecture is required to provide a clear structure, good daylighting and express the prominence and importance of the place. Though, the building often becomes an exhibit itself, an object to be examined.

In recent times, the planning of museum spaces have changed towards more interaction and involvement of the visitor. With the emergence of experience economy and new technologies and media, the focus on the total experience, including also the before and after the actual visit. The popularization of museum visits make the museums important public spaces. The functions diverse to include event making, education, research and as well as leisure and commercial activities.

"They (the public) will want to make connections between artefacts and their stories, just as documentaries do. It is for these reasons that the expectations of museum audiences must lead us to focus on the primacy of the visitor's experience." (Greenberg, 2005, p. 227)

Greenberg compares the modern museum to contemporary theatre, where the spaces belonging to the stage and to the audience flow completely together with no noticeable distinction between the two. In the same way the visitor should be able to occupy and activate all the museum space, instead of staying in the role of a passive onlooker. He calls therefore the museum a "performance space", where the whole experience from arrival to departure, is part of a performance sequence that involves the spectator. (Greenberg, 2005,)

For the architectural aspect of the museums it means, that the exhibition spaces demand more adaptable frames, with a flexible layout and priority given to multimedia. The space of the museum approaches the black-box theatre. For the architecture to contribute to the whole narrative, the exhibition concept must be consulted and integrated.

Topo des Terros, by Ursula Wilms

Holocaust Mahnmal, by Peter Eisenmann

Kalkreise museum, by Gigon & Guyer

Storytelling

The architecture will always be a co-narrator in the tale presented in the museum, thus the position taken might be various. The important discussion within museum architecture is to which extent the building design should "actively" contribute to the story told, or simply stay as a neutral frame to the exhibited content. The architecture must define it's relation to the exhibited objects and to the story that they are telling. In fact, no space can render itself completely neutral. Even the "simple, white box" will add its own layer to the story told.

The objects in a historical museum are often themselves merely an illustration of the complex historical and sociological processes that the exhibition tries to tell. Museums must give something in addition that storytelling through media and documentaries can't achieve – the sense of place, the physicality of the artefacts, the authenticity. The staging of them in the exhibition gives them a new layer of meaning.

Lee H. Skolnick discusses in his article "Towards a new museum architecture – Narrative and representation" (Skolnick, 2005) the differences between architectural representation and embodiment of the museum narrative. From a broad interpretation of the modernist "form follow function", he argues, that the embodiment of the story allows the initial ideas and visions to inform all design choices in the building, on the site, and the exhibition the like. As the "function" he means the very purpose of the building as a storytelling unit. Thus, the museum should strive to not only "tell" the story, but to "be" the story.

"...the human tendency to understand the world through the stories it can tell, and the potential that design holds to translate those tales into real-time, spatial experiences". (Skolnick, 2005, p. 129-130)

The three examples of museums seen on the right, all interpret historical events - the nazi totalitarian system, the holocaust and the battle of Valrus. With subtle means, through architectural abstract ideas and means like choice of material, landscape design or spacial sequences bodily experiences are created. They constitute an artistic whole on their own, but at the same time they symbolically refer to the past events, in a subtle, not too literal way.

Summing up, ideally, the building, the place and the exhibition content are integrated and create the total experience for the visitor. In that light, the museum architecture's central role is to establish the relation between story, artefact and place.

"Stories give the past a future."

Stephen Greensberg (2012, p. 103)

Historical background

Resistance fight

During WW2 Denmark was occupied by Germany from 1940 till 1945 and several partisan groups fought independently against the aggressor through sabotage. The resistance movement involved a few thousand people. Groups with different political orientations and size worked in both Copenhagen and Jutland. Their actions included mainly damaging the German supply lines by train track detonations, assassination of informers, production and distribution of illegal press materials and organizing the flee of Danish Jews to Sweden. Everyone joining the movement ran a high personal risk, with prison, torture, life in exile or possibly death as consequence. Eventually, the resistance actions cost the lives of around 150 people. Dramatical stories of the movement's most known persons are told in literature and film. (Danmarkshistorien, 2015)

The partisan fighter's resistance was in conflict with the official Danish response to the German invasion. The government chose the strategy of collaboration with the occupant forces, in recognition of the military inferiority of Denmark. By that they could minimize human losses and destruction, keep the state structures in Danish hands and negotiate about restrictions on civil society. The actions of the resistance fighters were outside of the official framework, and therefore illegal. They were not always well seen and causing many hardships in the relation between the government and Germans. Thus, the conflict involved more than just two parties. The internal relations are as big a part of the story as the fight against the German occupation power.

The resistance fight also had an influence on how Denmark was perceived by the Allied Forces at the end of the war. The collaboration policy ended in august 1943 due to, among other reasons, increasing pressure from the partisan organizations. The role of the freedom fighters became to prove Denmark as an enemy of Nazi Germany, and so to speak, "pull" the Danish over to the victorious side in the end.
The chapter of Danish history of 1940-45 contains many stories and problematics about individual and collective moral choices and their consequences. They ask a still relevant question of what does it mean to ensure common good and which methods are morally acceptable?

The assessment of the different positions towards the reality of war and threat, has been a under debate among historians and ordinary Danes until today. Opinions spanning from glorification to criticism have been uttered about both the politicians and the partisans. (Lund, 2014) The interpretation of historical facts interweaved with stories and "myths" and political rivalry of different parties. The still ongoing discussion only shows that wartime dramas never have simple solutions.

In relation to that, the identity and role of the museum came into question in a recent discussion whether it should be regarded as a memorial place for the fallen or should it be a general museum of the occupation times. The act of choosing and limiting the topic becomes in itself a statement about the past. Thus, the museum must be seen in a broader context of political and historical self-perception and identity formation. It is part of a longer process in time with changing views on how the past should be retold.

Searching for atmosphere

Regardless of the historical assessment of the political and individual choices during WW2, the period remains a disruption of ordinary social and moral order and the human costs it required remain a timeless topic. In search for an expressive and bold atmosphere for the museum, the view must turn on the human and emotional aspects of freedom fight. To reach an understanding of the resistance fighters' mental world and experience, poetry is brought in as inspiration.

The young poet Morten Nielsen wrote during occupation time and his participation in the resistance movement deeply influenced his works. He published only few of his poems in the journal "Hvedekorn" and in a collection "Krigere uden våben" in 1943 (Knudsen, 2006). All though he only lived 22 years, his name entered into Danish literature history.

Poetry of Morten Nielsen, encapsulates an evident consciousness of death and fragility of life. Still, as a firm layer underneath the fear and tribulations a great vitality shines though. The tension of being in a turning point, the quiet of a momentary peace and expectancy of a dramatic confrontation is all the time present. (Bredsdorf, 2002)

This state of gloom and fear, but with glimpses of light on the horizon, is the universal human condition, further magnified when subjected to dramatical life events. The atmosphere for the museum visit can use the poem as illustraiton. It should in the same way be grave and gloomy but life-affirming. The building sets a tone for the experience, before the visitor reaches the exhibition. The atmosphere cannot and should not try to recreate a feeling of wartime, but still convey the core essence of stronger reliving of life's aspects in the ubiquity of death and destruction. The museum will in that way also leave the interpretation open regarding the content, legacy and moral judgements over the historical events. The visitors will be invited into the search for meaning and engaged in the narrative.

"I hear only my heart beating"

Morten Nielsen

JEG HØRER KUN MIT EGET HJERTE SLAA

Her vokser Gran og hvide Birketrærer,
en Sommernat igen. Bag vaade Straa,
der leger som en Hvisken mod min Mund,
er Rummet nært og Himlen dyb og blaa
- jeg hører kun mit eget Hjerte slaa.

Jeg ligger mellem alle mine Ting.
I Morgen gaar de under hver og een
i al den Angst, der rejser sig paany -
paany skal Skæbner briste i et Drøn,
og to Par Hænder vristes fra hinanden,
og Angstens gale Hunde slippes løs.
Det sker igen -
og jeg er vaabenløs.

Jeg ligger mellem alle mine Ting.
I Morgen gaar de under hver og een.
Der kryber Fingre sammen om en Sten,
og Hænder krummes om en Lansestang.

Der stiger Angst
før vore Dages hvide Sol,
og jeg har hørt, naar Morgenhanen gol
for tredje Gang.

Der vokser Græs i Nat paa denne ø.
I Morgen spirer Angsten for at dø
igen i Hjertet - og vi er igen
paa Vej, paa Vej, og ingen ved hvorhen.

Men her er Gran og stumme, hvide Trær.
Jeg hører kun mit eget Hjerte slaa.
Og Himlen kommer mig saa nær, saa nær
og staar som Dybder om de vaade Straa.

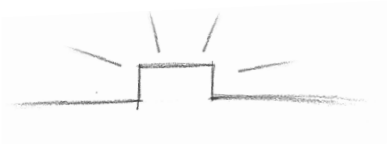
Morten Nielsen

Brief

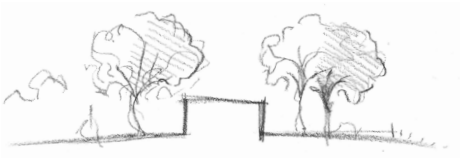
The competition brief (Nationalmuseet, 2014) sets out guidelines for the museum design with a descriptive specification of the functions. The museum's architectural attributes, **spatiality** and **atmospheric qualities** are of great importantance.

The suggested diposition divides the museum into **an arrival and an exhibition zone**. The arrival zone is of public character with a café, servicing and staff functions. The outside areas should be included in the use of café and foyer facilities.
The exhibition spaces should offer flexibility and robustness, as well as an interesting spacial sequence. The daylight intake should be limited. The exhibition zone is separated, but attention should be payed to how the **transition** between the two zones takes place.

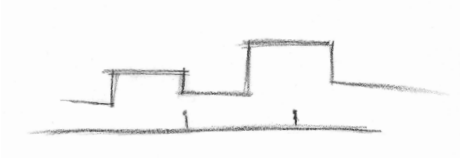
It is a wish that the building is eye catching, **recognizable**, and stating its purpose in the urban space. The **placement in the park** should lend character to the buillding. The brief suggest a proposal for the re-treatment of the entire park area with focus on the transtion from Kastellet to the city with attention on the arrival situation and the historic context.
A maximum for the footprint is set to 1000 m2 above ground.



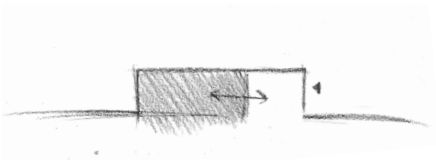
recognizable building



a museum among the green



spatially interesting

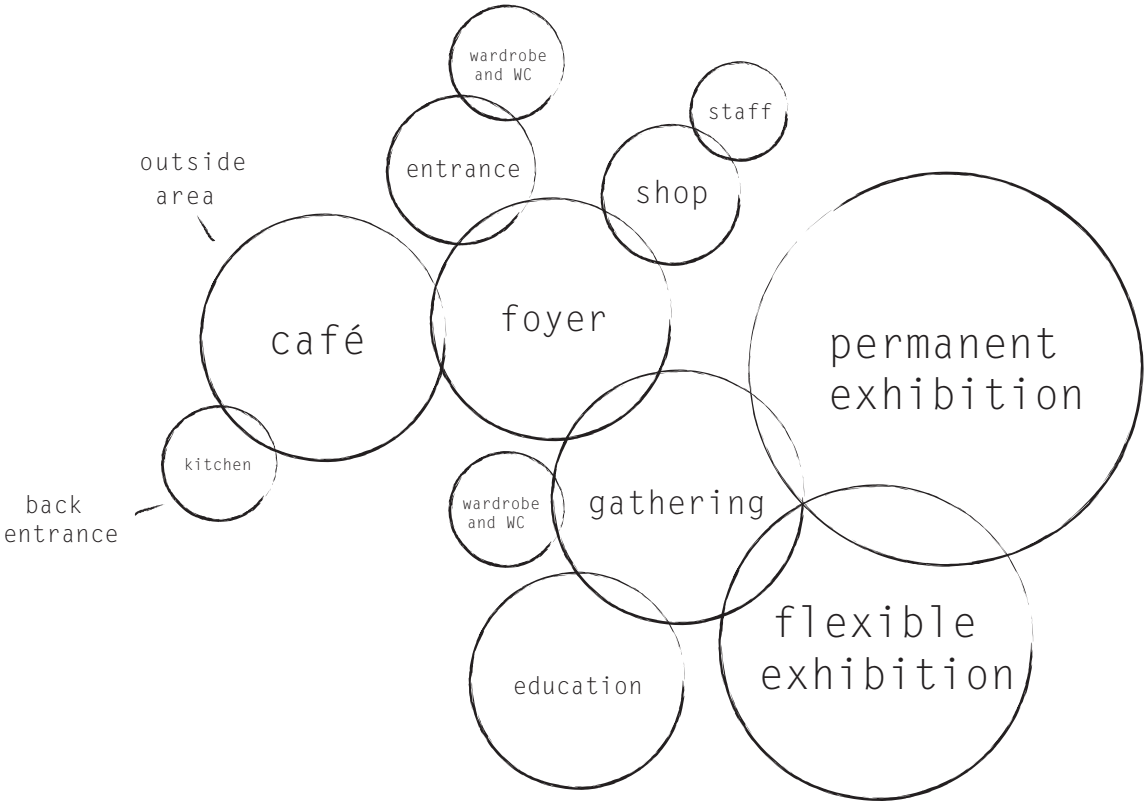


connecting the arrival and exhibition zone

Room programme

Based on the competition material (Nationalmuseet, 2014) the functions needed are specified. The functionality of the museum is about setting the exhibition spaces and the functions servicing them in relation to eachother.

	Area - netto [m2]	Daylight priority	Nr of people	Min height [m]
Arrival				
Entrance	10	***		6
Foyer	70	**	-	6
Sitting area	70	***	30	6
Café	100	***	40	6
Kitchen	20	**	2	2,5
Toilets for café	20	*	-	2,5
Lift	5	*	-	2,5
Cleaning room	3	*	-	2,5
Shop and info	30	**	1	2,5
Staff room	20	***	4	2,5
Stair	80	*	-	-
Exhibitions				
Temporary	800	*	200 pr day	3 till 10
Permanent	1500	*	200 pr day	3 till 10
Exhibition services				
Gathering area	80	**	50	3
Lecture room	70	*	50	4
Workshop	30	*	3	4
Toilets	70	*	-	2,5
Cloackroom	30	*	-	2,5
Technical room	30	*	-	-
Total	3038			


wardrobe and WC
staff
outside area
entrance
shop
café
foyer
permanent exhibition
kitchen
back entrance
wardrobe and WC
gathering
flexible exhibition
education

Usergroups

The museum has a **memorial function** for those with a personal relationship to the events of the war, as well as in relation to official events and celebrations.

Groups of tourists and other visitors who seek the experience of a museum visit as a social activity. The museum spaces should be attractive and besides the exhibition experience also give space for **relaxation and socialization**.

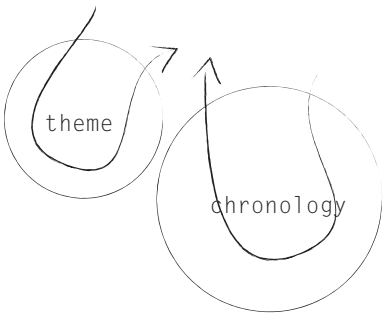
Educational activities are also a significant part of the museum's role. School groups will be a frequent visitor, needing space for **educational situations** and gathering in groups.

Exhibition concept

The National Museum (Nationalmuseet, 2014) provides an initial concept for the exhibitions. The overall structure consists of **two visitor paths** – the permanent, chronological narrative, divided into different zones, and a more flexible part for temporary exhibitions of theme character. The potentials for presentation of the exhibits within the space and how the building will brace it's content are important focus points.

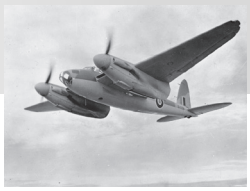
The two types of exhibition space should be clearly distinctable, but not completely separated, so that the visitor can switch between the two. In the **permanent part** emphasis is put on staging different atmospheres and environments and give an impression of the past times. The narrative is a chronological succession, starting before the war, leading through the years 1939-1945, and ending with the liberation and perspective of the future to come. The **temporary exhibitions** should be more flexible and relate to fx current topics.

The exhibition will contain many **authentic objects** of dfferent sorts, many of which described as space demanding as the air craft model, original tram, parachute or armored car. The daylight in the exhibition area should be restricted. The expected number of visitor is around 200 pr day, or 400 for bigger events.



1939

1945



Project site

Placed on the edge **between dense city and green space**, the new freedom museum will mark the node of many attractive pedestrian routes that already connect key points of the inner Copenhagen. The **historical traces** in the area create a solemn atmosphere and play an important role in the identity of the city and the nation. Surrounded with park areas, coast promenades and well connected to public transportation, the spot is an attractive place for a new museum.


S - tog staion
Kastellet
Amalienborg
Harbour bus
Pedestrian paths
Accsess roads
Regular roads
Main traffic road
Train (S-tog)
Bus stops

Transportation network

The site is well connected to the public transportation system, located only 800 m away from the nearest, local train station and less than 300m from a bus stop. The ferry-bus also has a stop in close proximity, connecting the area to the opposite side of the harbour.
The surrounding streets are quite calm, functioning only as access roads, which makes biking and walking safe and easy. Taking the car is in general not necessarily the fastest option in the city centre, but when needed a couple of parking places are available near the site too.
It is worth mentioning, that the area in general is very pedestrian friendly. The many walking paths crossing the park and continuing to the Kastellet or the harbor promenades enhance activity and urban life.

Green spaces

The site is located in the Churchill park, that together with Kastellet are the quite big green patch in the city neighbourhood. Kastellet is a remarkably well preserved part of Copenhagen's fortification system built in the 17th century, today a part of the inner park-belt surrounding the historical inner city (Kbh Kommune, 2003). As a recreational space and destination for long walks it is popular among both Copenhagen's inhabitants as well as visitors. Besides being a rich green space, it offers interesting spatial experiences, such as a views to the city or the harbour from the elevated ramparts, proximity of water in the moats and a peaceful inner space with in the protecting earth embankments.

Urban typologies

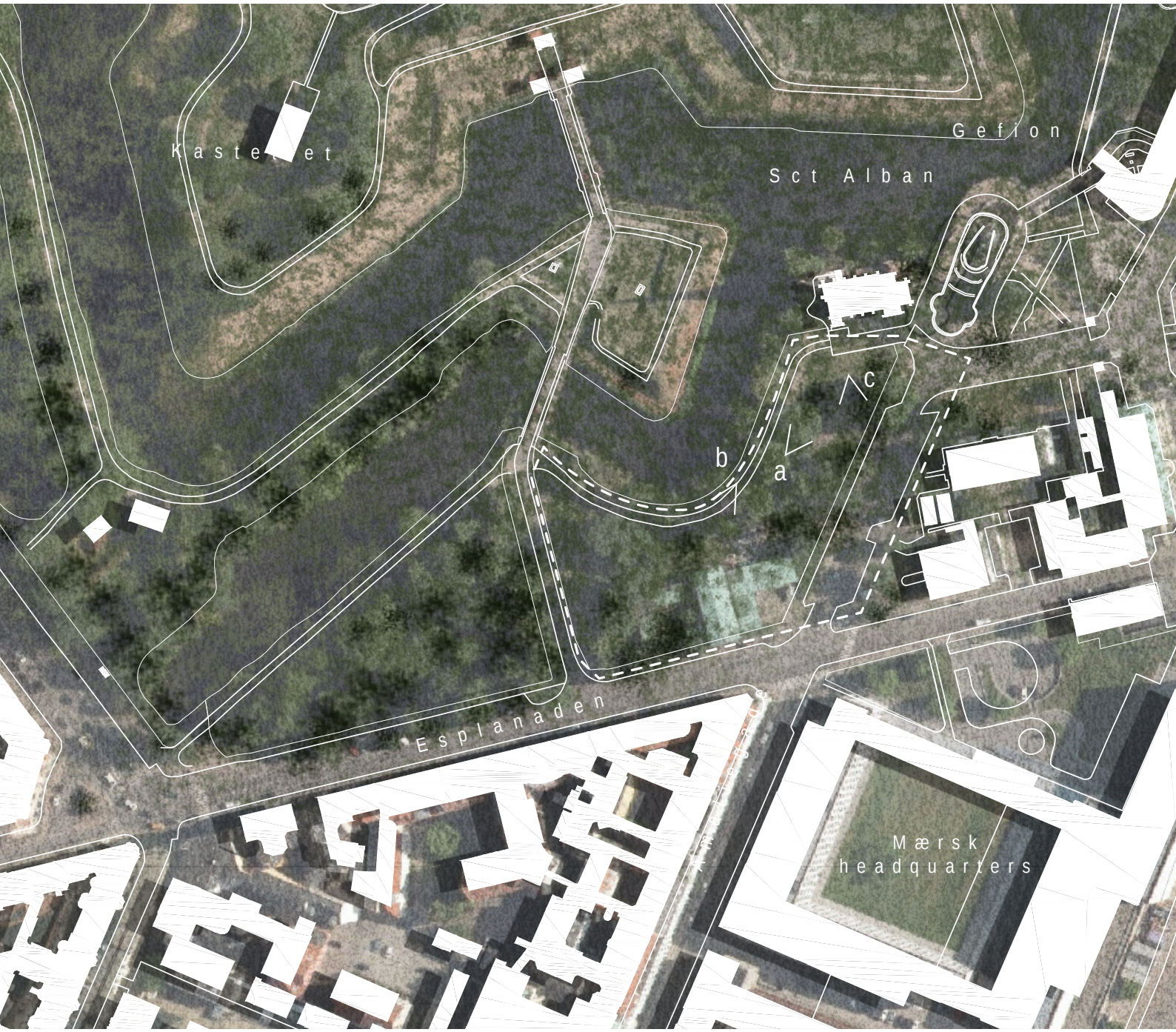
The city area, south of the site, is part of “Frederiksstad” built according to a baroque city plan (Kbh Kommune, 2003). The streets are organized in a grid structure with strong axial views. The building mass is structured as dense blocks, around six stories high, but with varying façade expressions. The city space ends rapidly with a façade front, where the green spaces begin, with Esplanaden and Grønningen as edges between the two.

Historical spirit

The project site is located very centrally, in proximity to many tourist attractions and landmarks of the city. For example the Amalienborg castles, the Marble church, the little Mermaid, Danish Design Museum are less than 1 km away. The museum's location is so to say another stop on the routes connecting the spots mentioned above, which is beneficial for attracting visitors and drawing attention to the museum.

The project area has many traces of different historical times and events. The fortification complex, the many memorials in the park and around, the old city structure and the proximity of royal residences give an atmosphere of importance of a capital city and a feeling of layered history and identity embodied in the place.

The museum will on one hand be suitable here, on the other it will have to make another puzzle piece fit into this complex context in space and time.



1:2000 (photo from Arealinfo)

Building plot

The building site itself is part of the green space of Churchill park, only divided by a moat from the bigger Kastellet area. With the street crossing of Esplanaden and Bredgade to one side, and with the park pathway on the other, the site has two different urban spaces to respond to, but no back- and front side, as it can be approached from either side.

The surrounding buildings are very different in character. Towards south the block structure of the city fabric ends with as a sharp edge of continuous, yet different facades, four to six stories high. The street spaces south of the site are clearly defined, but towards west the neighbouring buildings not so densily placed. They are more like objects placed in open space, allowing glimpses to the water side.

The Maersk headquarters stand out as the only modern building in the near surrondings, in comparance to the 18th and 19th century architecture around.

The most attractive views from the site are towards north, where we find the fortification complex, and North West, where the church of Sct. Alban's is located (view a).

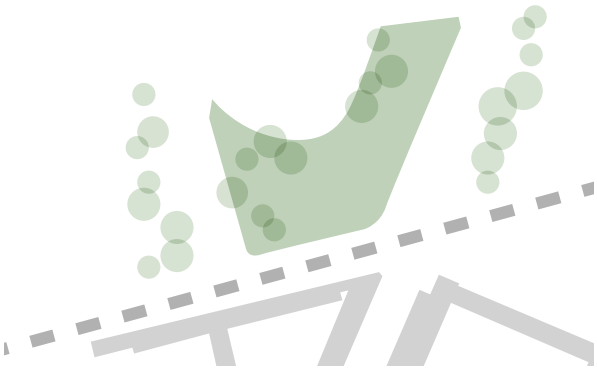
a) View to the north, towards Sct Alban church

b) The park path on the northern boudary of the site

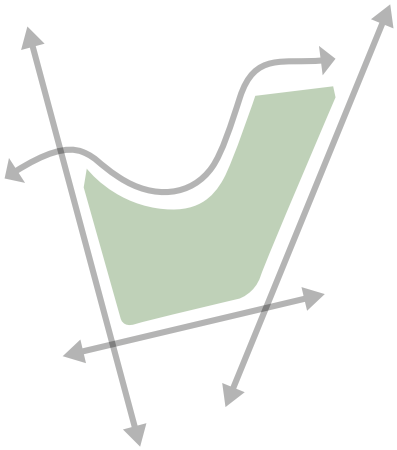
c) The edge between street and park, with a view towards Mærsk headquartes.

Summary

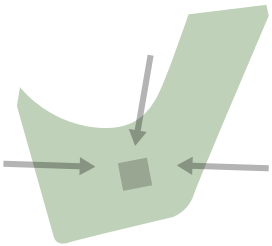
In short, the project site is located in a border space where areas with different characteristics and atmospheres join together. One of the great potentials is how friendly the area is to **pedestrians**. The proximity of **recreational spaces** and touristic sights will keep the place well visited and the museum exposed to a flow of many passers-by. The area is also a place with a strong **historic identity,** bearing traces of many époques, constituting a frame of national heritage in which the museum will be inscribed.



The **division** between city and park should be **strengthened.**



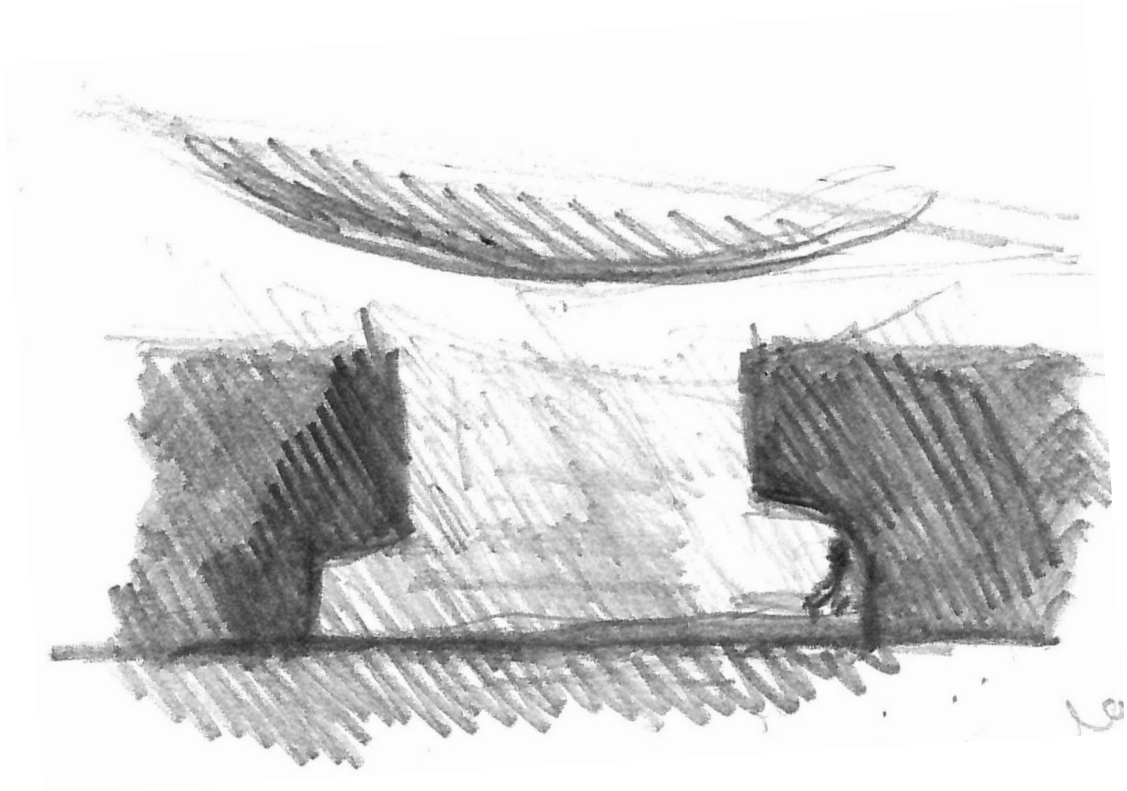
As the building is located at a node point of many pathways, it must have no backside and be **approachable from all sides**.



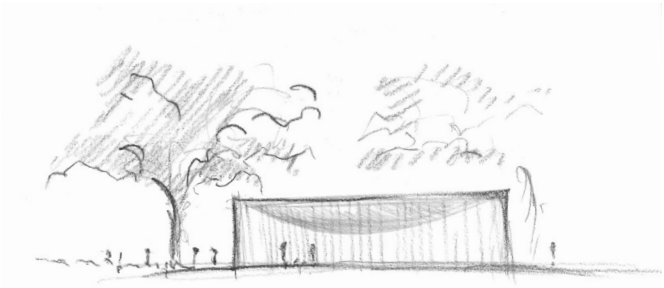
The building should be readable as an **object** among other objects of strong character in the context. Placed as a **point in the landscape** of the green and creating a public space, inviting for

Vision

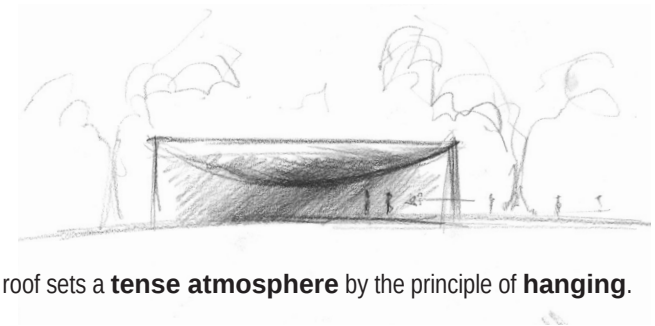
The new Freedom museum becomes a **public space** in the Churchill park. It passes on the **narratives** from wartime to today's visitors through spaces for immersion and reflection. It connects the complementing realms of everyday life and existential reflection by setting a **somber atmosphere**.



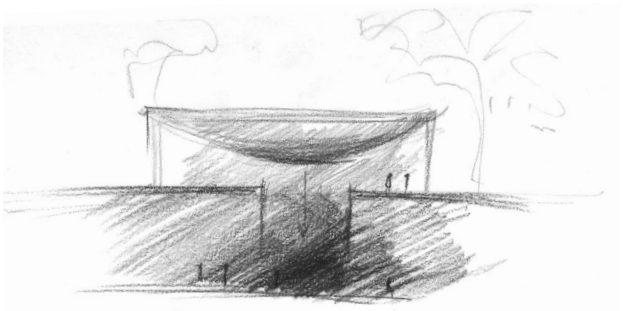
Concept



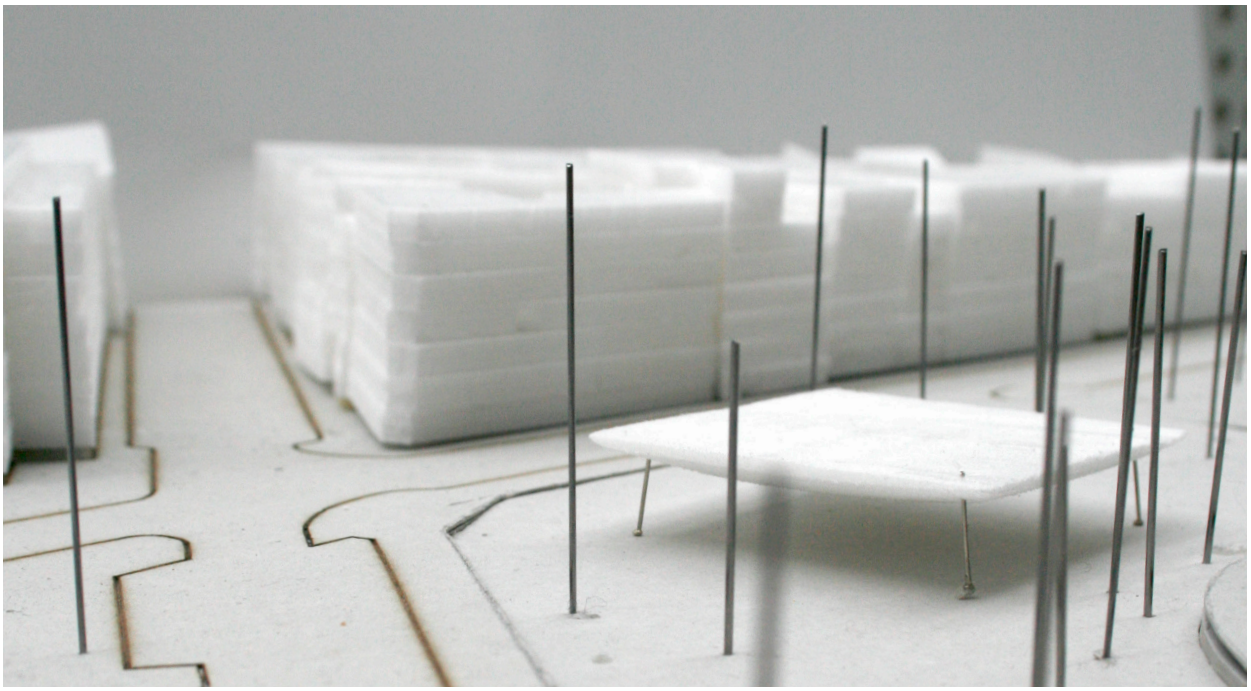
The roof establishes a **space in the park**.

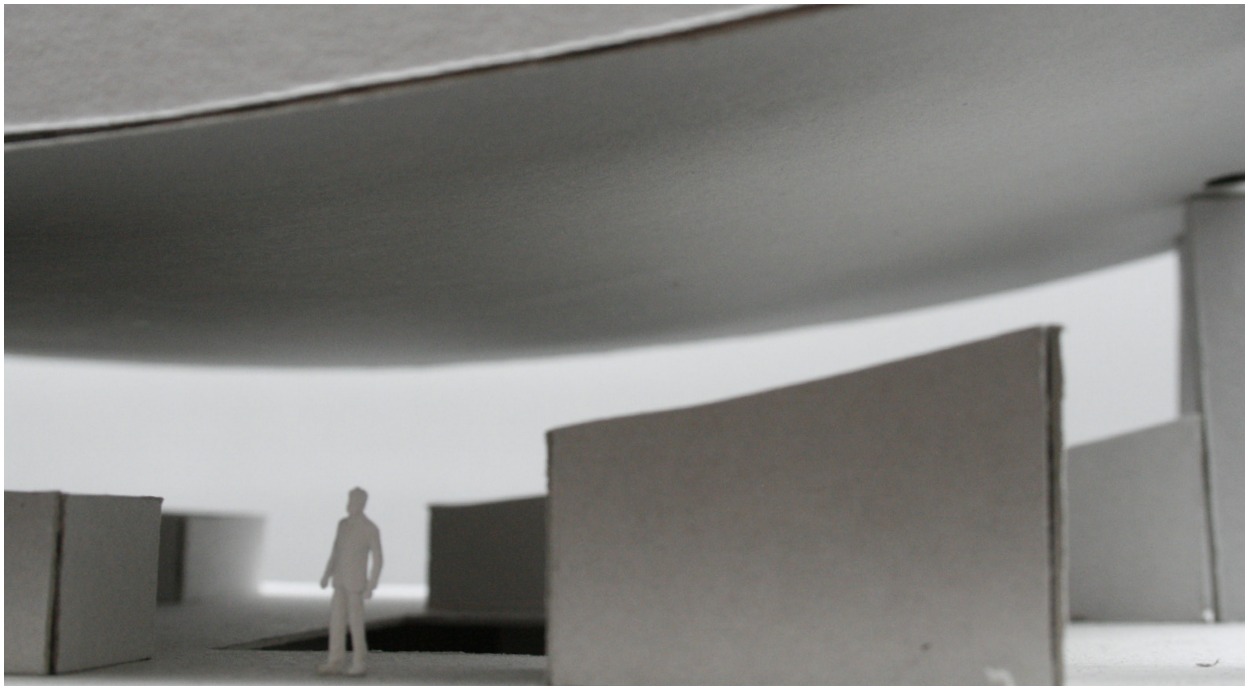


The roof sets a **tense atmosphere** by the principle of **hanging**.



The roof stages the **downward movement** to the underground exhibition spaces.





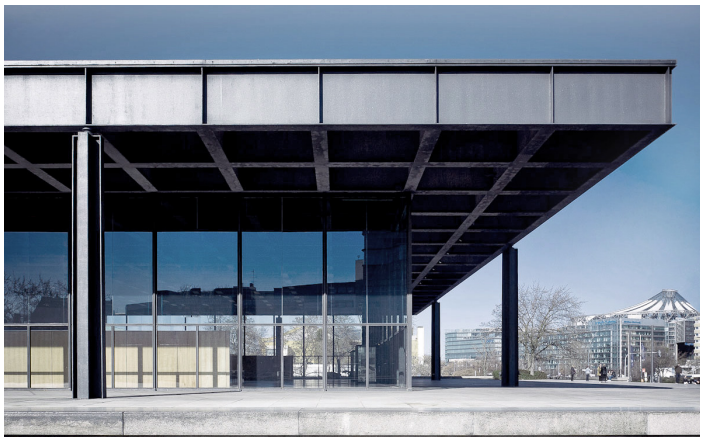
Roof concept

A roof is a simple **space creating** object. It marks a place in the park landscape. The alluring image of a hovering surface defines the museum as **object** on the green surface. It carries monumentality and landmark quality, suitable for a museum typology placed in these surrondings.

A roof in itself is a strong architectural edifice referring back to the archetype of a baldachin raised over important objects or persons as a doubling of the sky. (Roesler 2013) It creates a well defined, but still open, fluid space, as seen in the examples of the designs of Alvaro Siza and Mies van der Rohe.

At the same time, the dramatic, **omnious atmosphere** is to be set by the roof's shape, its material and graduation of space from high to lower. The Sct. Hallvard church is suitable as a reference for this sombre interior with an inherent feeling of **tension**.

The roof has then a double role as **place and atmosphere creator**. The constructive method combined with the gloomy atmosphere will be the **main architectural parti** of the museum.



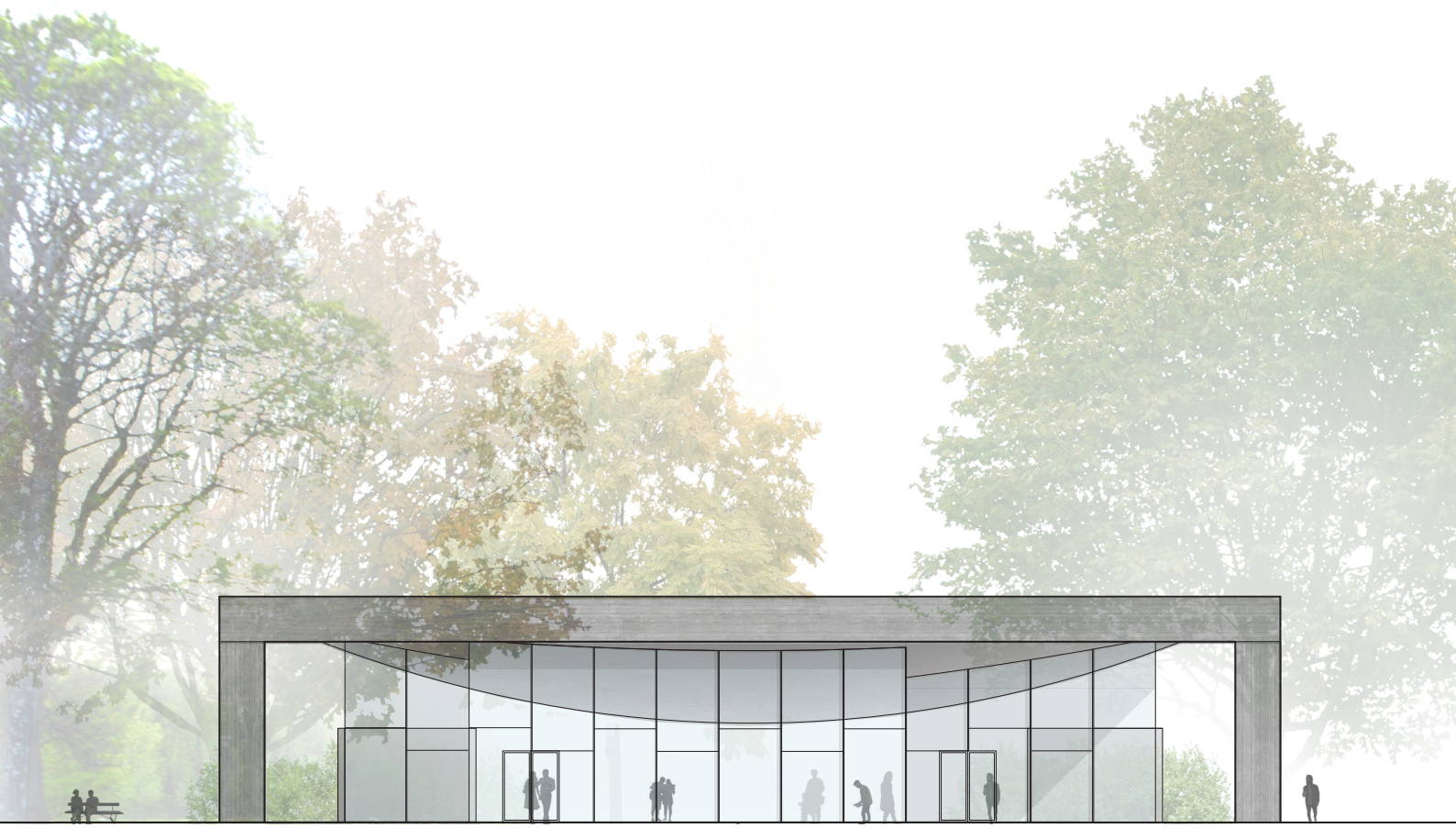
Neue Nationalgallerie, by Meis van der Rohe

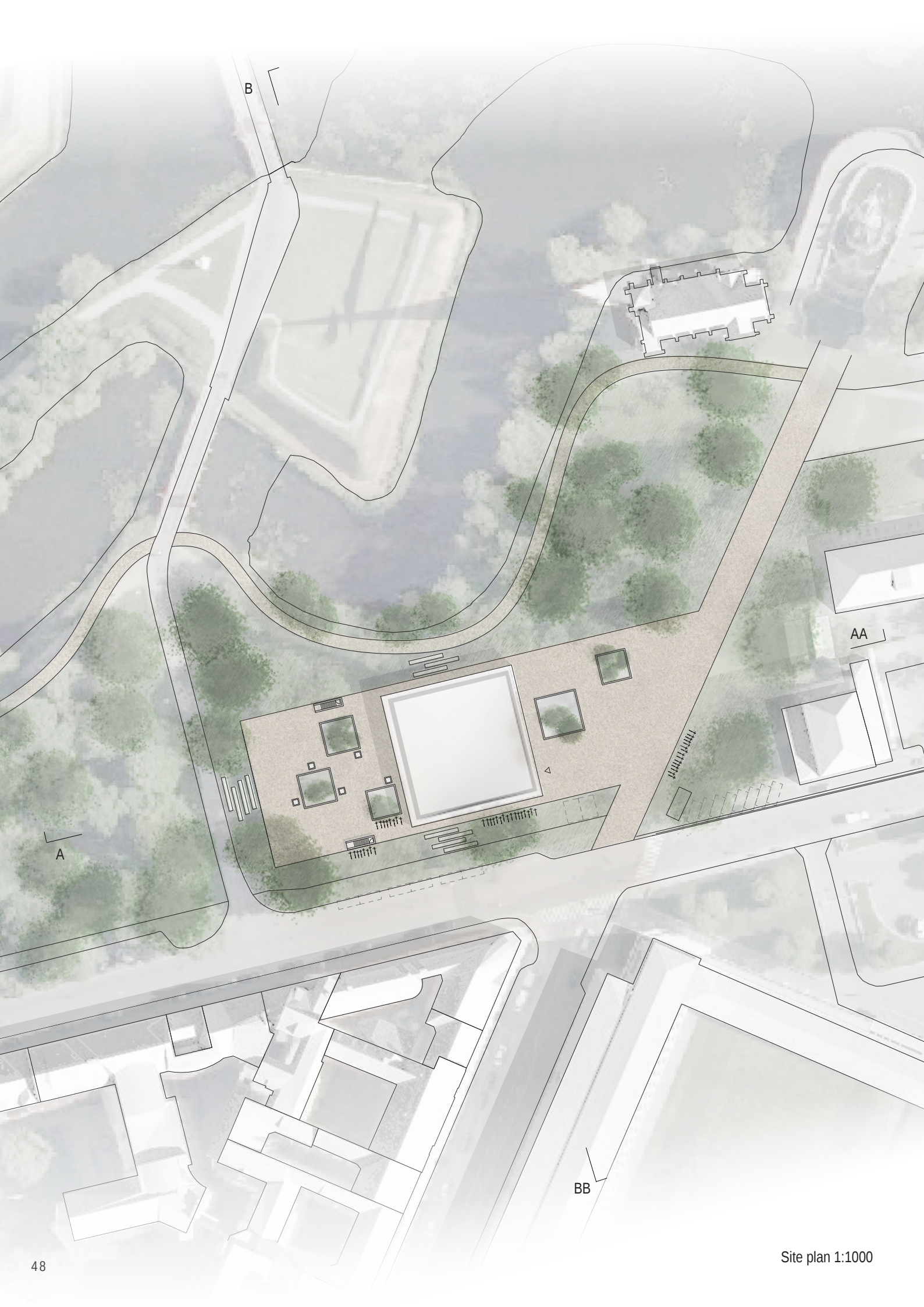
Lisbon pavillion, by Alvaro Siza

Skt. Hallvard church, by Lund+Slaatto Arkitekter

East elevation 1:2000

Presentation

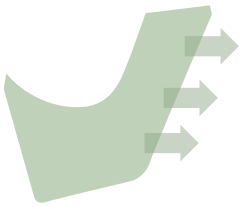




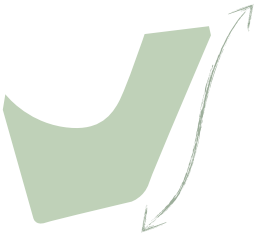
Site plan 1:1000

Outside areas

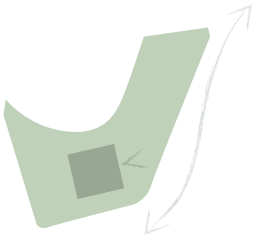
The museum is placed between the edge of the city and the first moat of Kastellet. The new park promenade leads the visitors through the green space and towards Gefion fountain by continuing the axis of Amaliegade. A square in the front of the building, addresses the promenade to lead the visitors towards the entrance.
Towards west a large terrace space is created as an extension of the indoor functions and with connections to the surrounding walking paths. The spaces are furnished with elevated plant beds. They offer, together with the roof overhangs of the building, different zones for stay in the open park space.



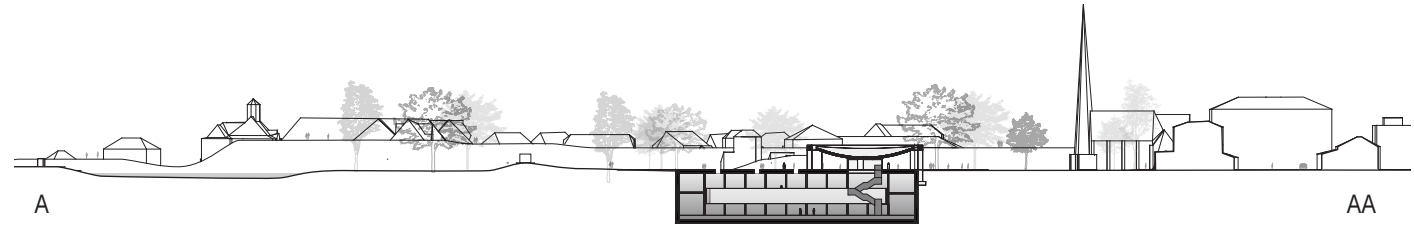
The park area is **extended**.



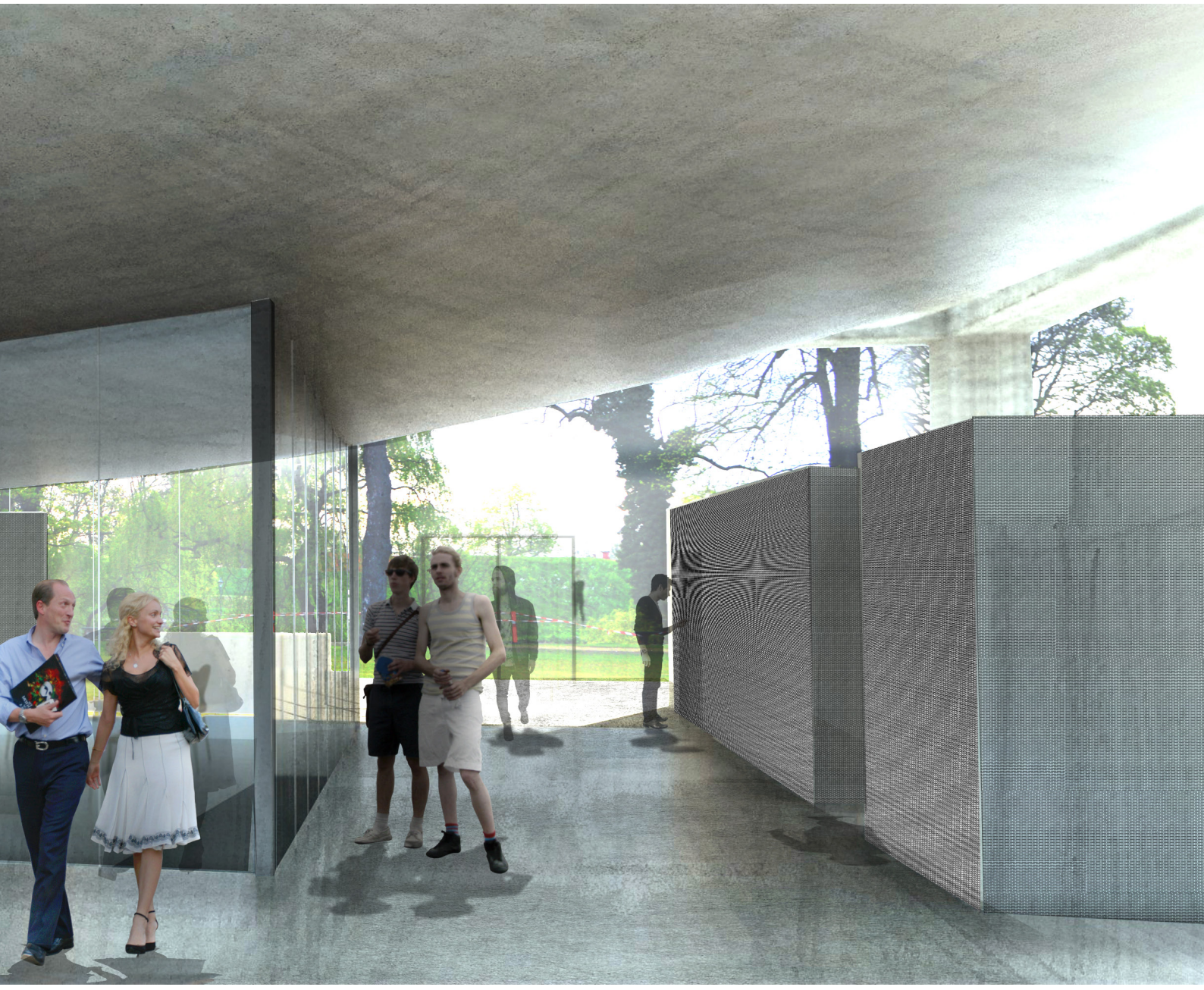
A new **pedestrian promenade** is etablished.

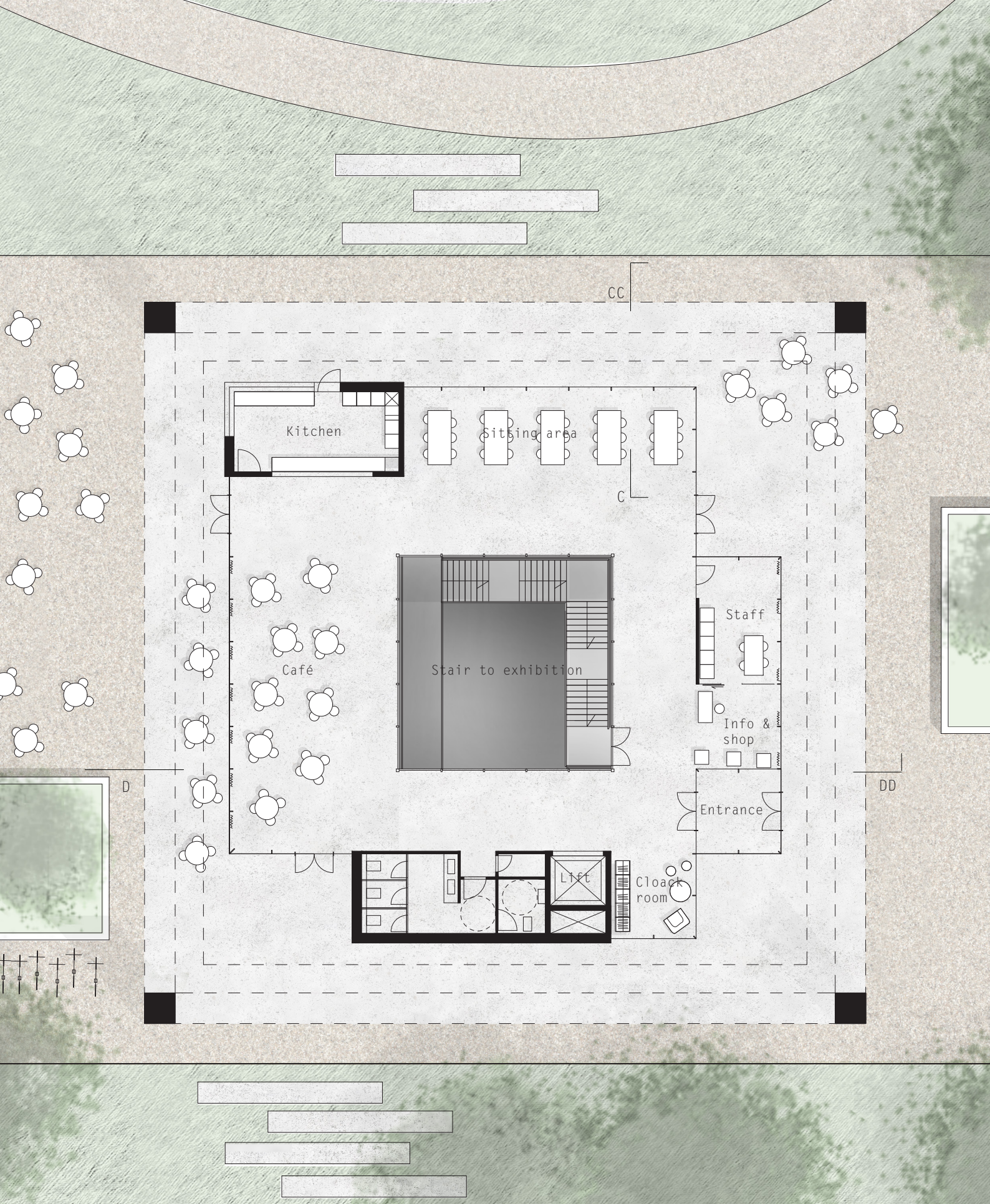


The **main entrance** is oriented towards the promenade.



Urban sections 1:2000





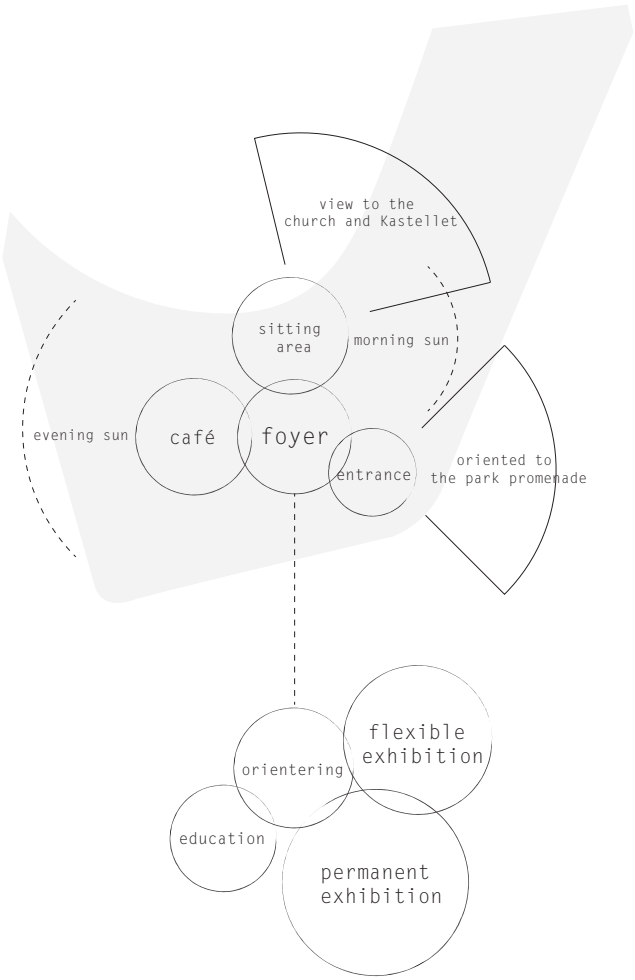
Ground floor plan, level 0 1:200

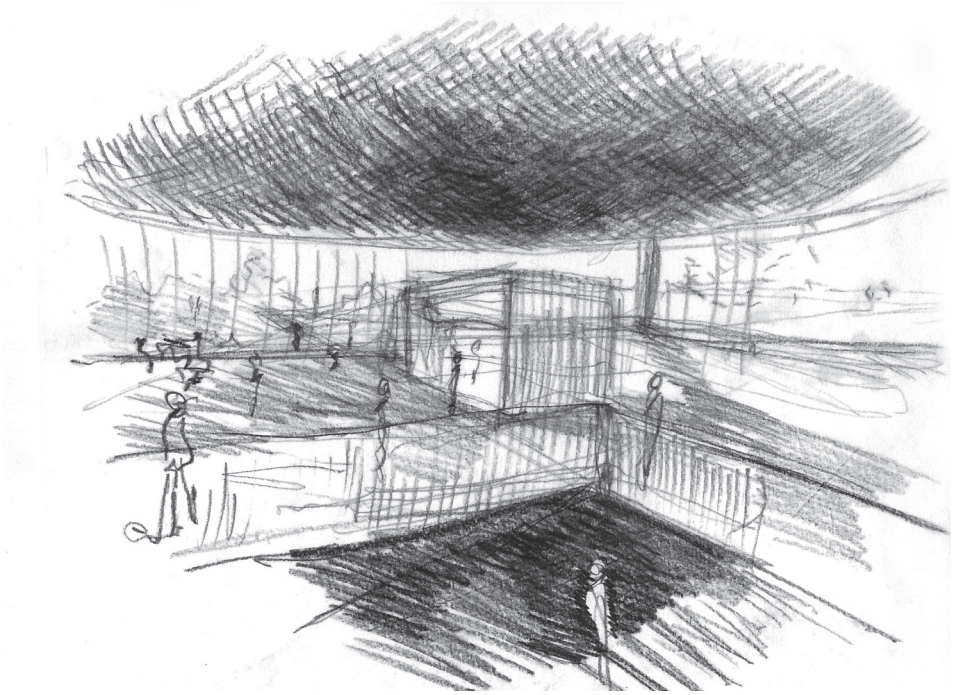
Foyer space

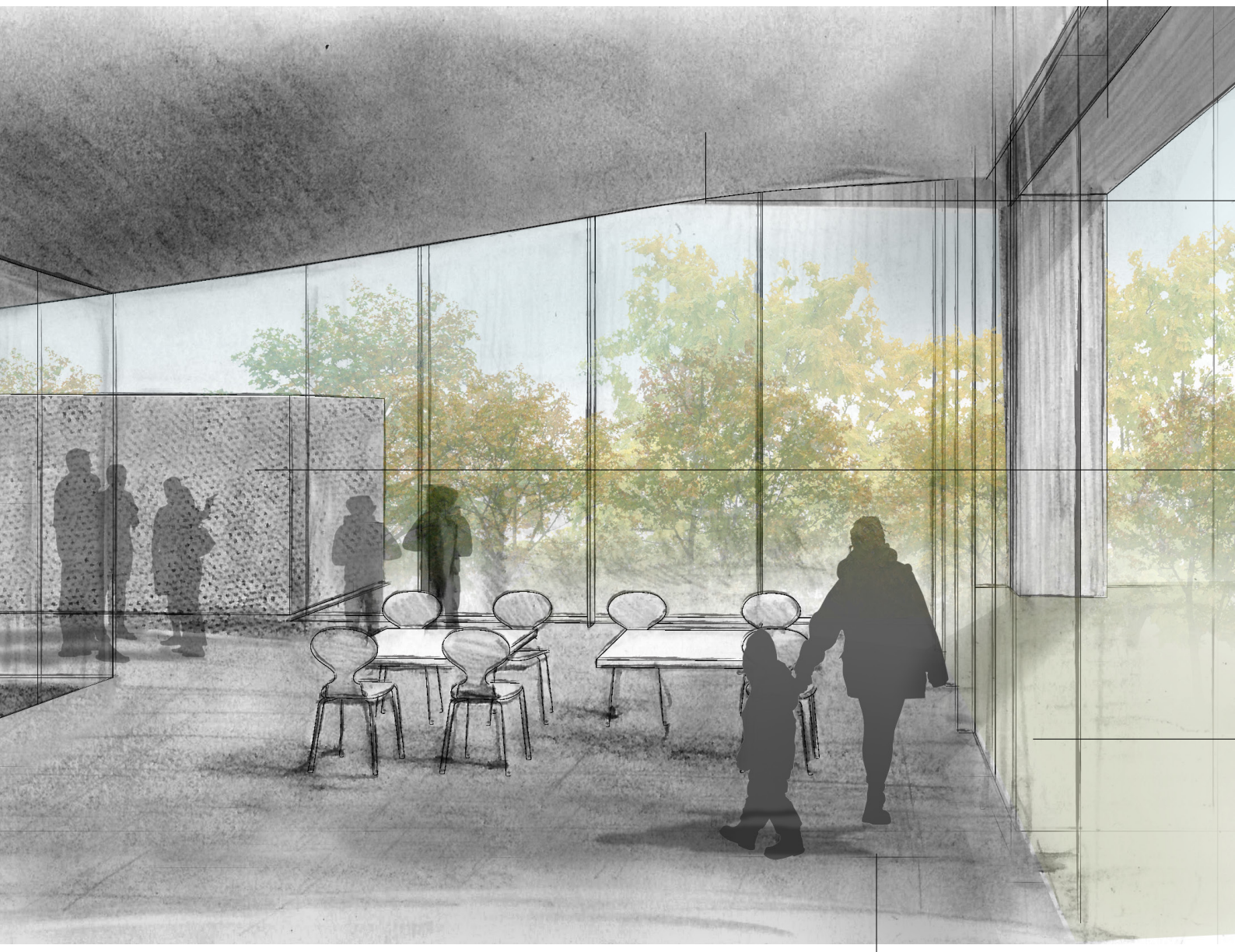
The open plan of the ground floor gives a free circulation between the respective functional zones. The entrance leads into the foyer space from the eastern side. To the left are the pragmatic functions of lift, toilet and cloakroom, to the right the information point with shop and opposite the entrance leading to the exhibitions. Going further ones comes to the café sitting area, with the kitchen standing independently. The café can be extended to the sitting area for bigger events.

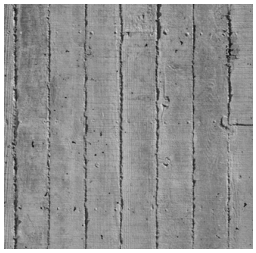
The functions are placed on the site according to different qualities. The sitting area in the foyer will be used mainly be school classes in the mornings, whereas the café mostly be other visitors in the evening time. Therefore their orientation takes the sunlight into account. To minimize the footprint of the building, exhibitions and their assisting functions are placed under ground. The space can then remain open with views to the surrounding park to all sides. The setbacks in the facades offer covered outside that in the summer become an extension of the inside space.

The foyer is transparent and open, but dominated by the curved roof. The sombreness of the space makes the museum a space out of the ordinary, everyday life. The graduation of space and the tense expression set an atmosphere as a prelude to the museum exhibit. The looming tension stages the gradual transition from the open, light entrance to the gloomy exhibition spaces. From any point in the foyer, the attention is guided towards the central stairwell leading to the exhibitions.

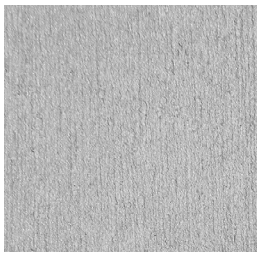




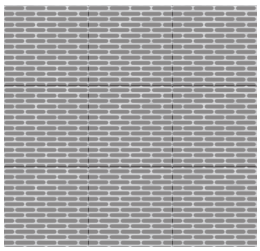




Massive concrete
with wood formwork traces



Rough trowelled shotcrete



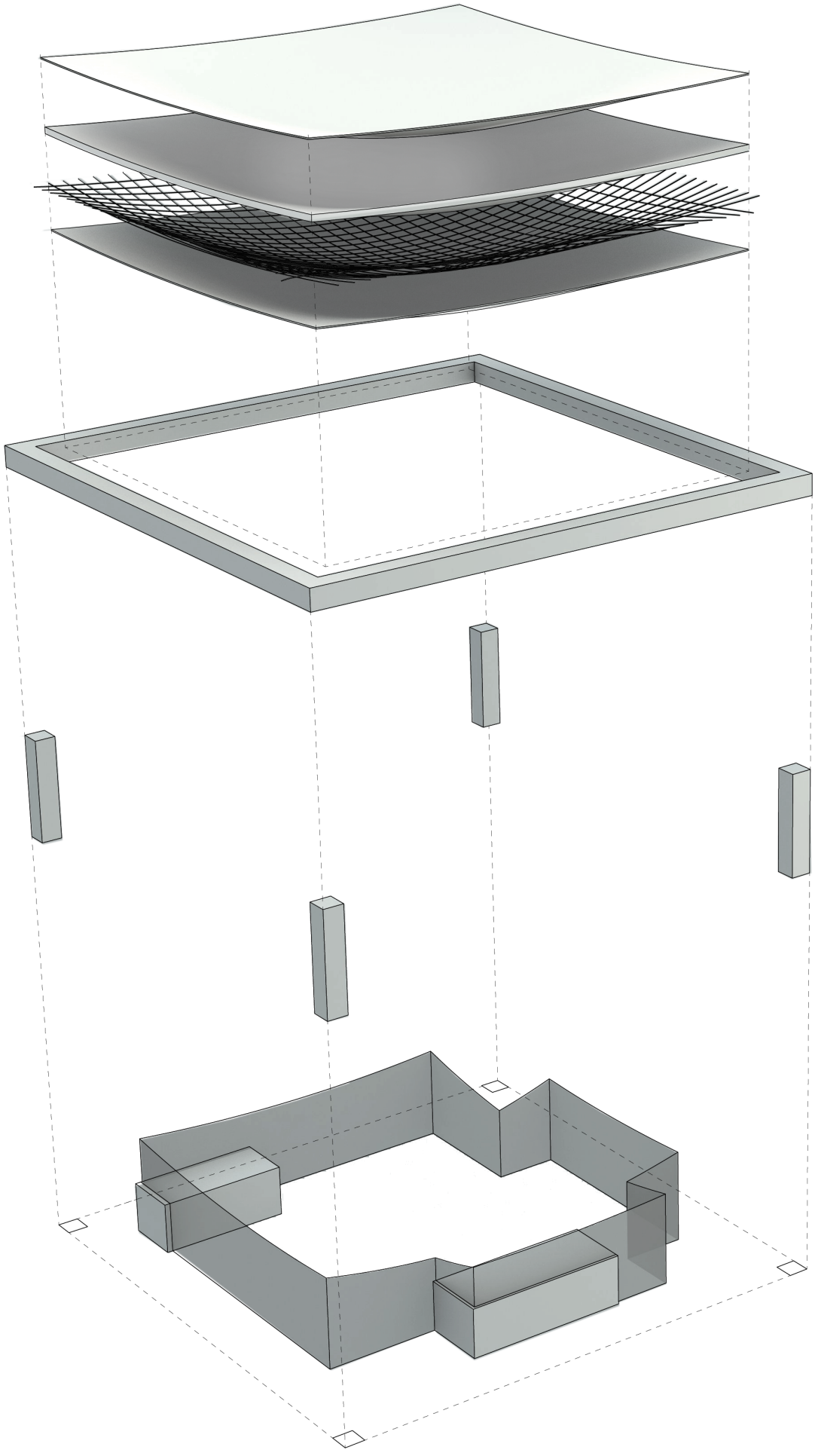
Perforated steel sheet

Structural glazing

Grey stoneware floor tiles,
without grouts

Materiality

The choice of materials underpin the atmosphere with cold, grey and calm tones. The different tactile characters contrast with each other and give a varied experience. The exposed concrete designate the bearing parts, while lighter claddings signal which building parts are non-bearing. Some of the materials are repeated on the different levels of the building to create some links between the spaces of otherwise so different characteristics.



Structure

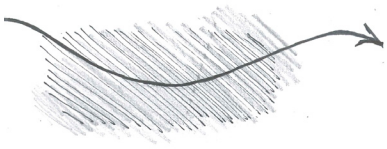
The museum's roof structure is the main architectural element defining space, atmosphere and construction method. The roof itself consists of bearing cables with an internal and external cladding layer of shotcrete, with insulation between. The cables are anchored in the frame that by its stiffness takes up the forces from the horizontal pull of the cables as well as the roof weight. The edge frame stays in equilibrium and is then supported on the corner columns.

The entrance space on ground level gains its character from the bare concrete surfaces in the interior. Concrete is chosen as the main building material due to its numerous possibilities to create sizeable constructions. In the design the concrete is used in two ways - as structural, massive material, as well as a light surface cladding. This difference is emphasized by the contrast between the orthogonal and the organic shape idioms of the frame and the roof structure respectively. The building achieves a duality in expression. From outside the constructive frame is in the forefront, but the curving surface can be sensed through the glazed facade. Inside, the bulging roof sets the atmosphere, while the geometrical frame is almost hidden from sight.

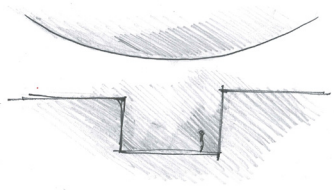
The shape of the roof comes from the hanging principle, from the fact that the gravitational force acts on the cables. The intention of establishing a looming atmosphere of the war narrative is in that way embodied in the construction itself. Hence, the structure conveys the museum content and establishes the building's identity.

Structural concept

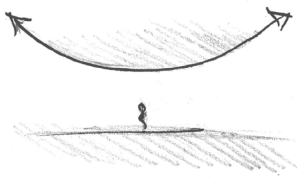
Museum visit as journey between light and dark



A downward movement and a convex roof element

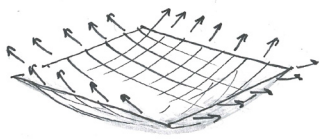


Convex shape from catenary curve

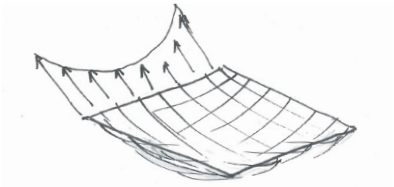


Double curving suspended roof surface

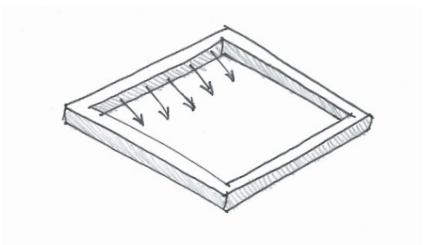
Bearing cable structure

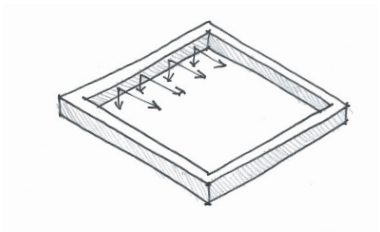


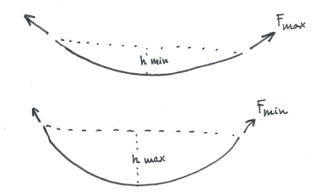
Cable tension varying with the sag



Cable pull at an angle, decomposed as horizontal and vertical forces.

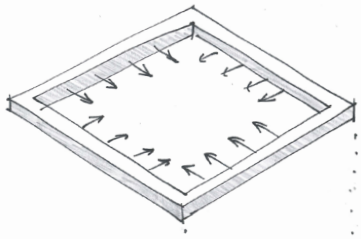




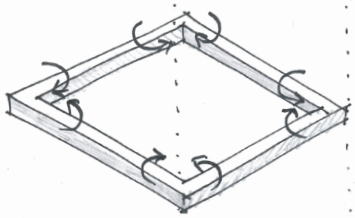


Static behaviour

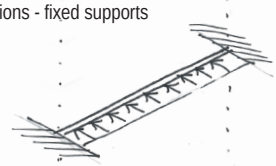
Horizontal forces



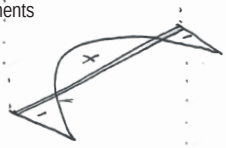
Moments in horizontal plan



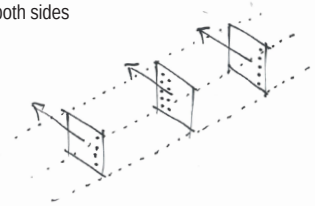
Stiff corner connections - fixed supports



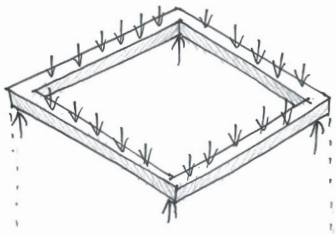
Positive and negative moments



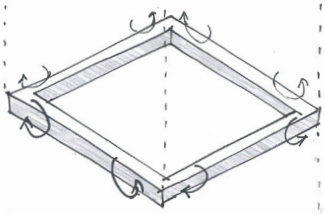
Reinforcement in both sides



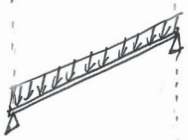
Vertical forces



Moments in vertical plan

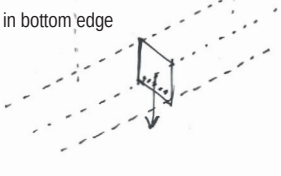


Simply supported beam

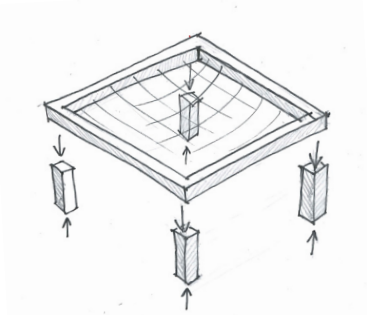


Positive moment

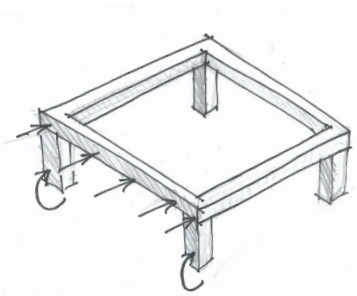
Reinforcement in bottom edge

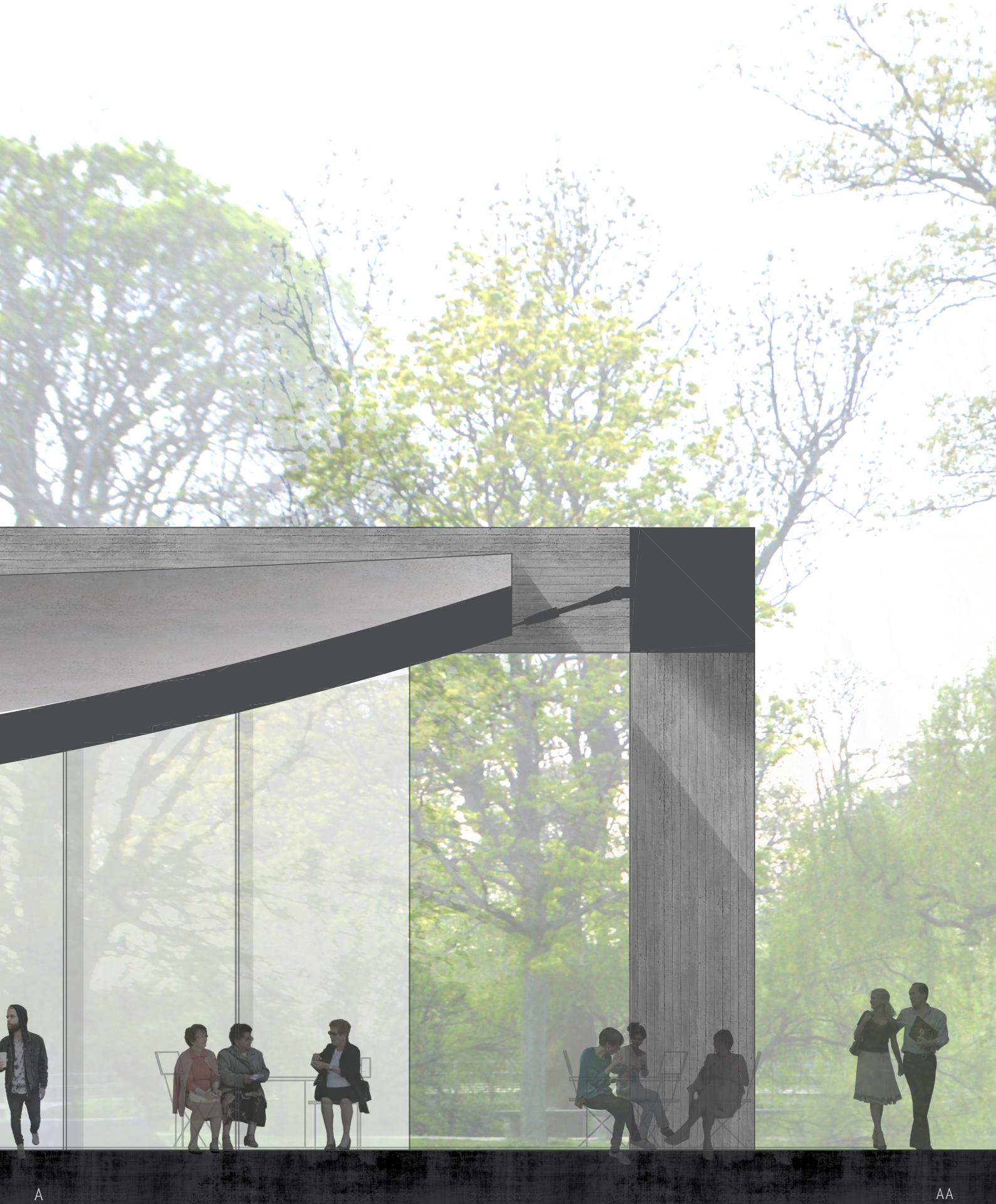


Simple column support



Moment stiff column footing

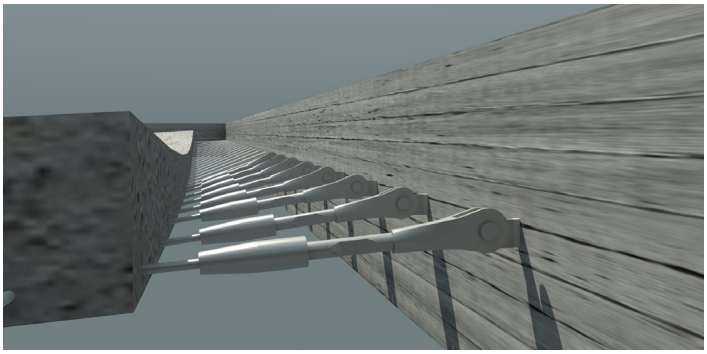


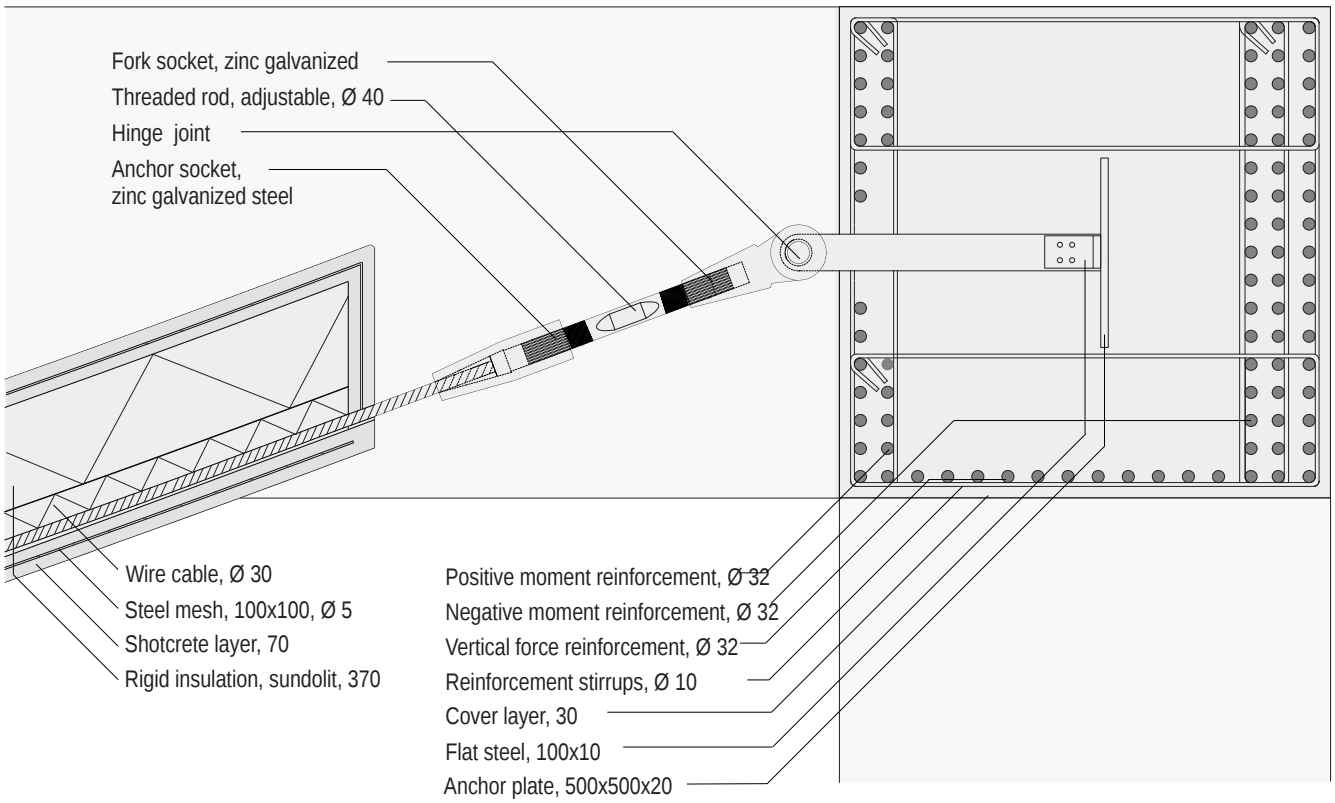


Section 1:50

Detail

The joint between the frame and roof itself expresses the relation between the bearing and the borne parts. The gap visually separates the thin roof surface from the solid frame, exposing the bearing cables. It reveals the constructive principle of the whole edifice, by making the roof and frame readable as two elements.

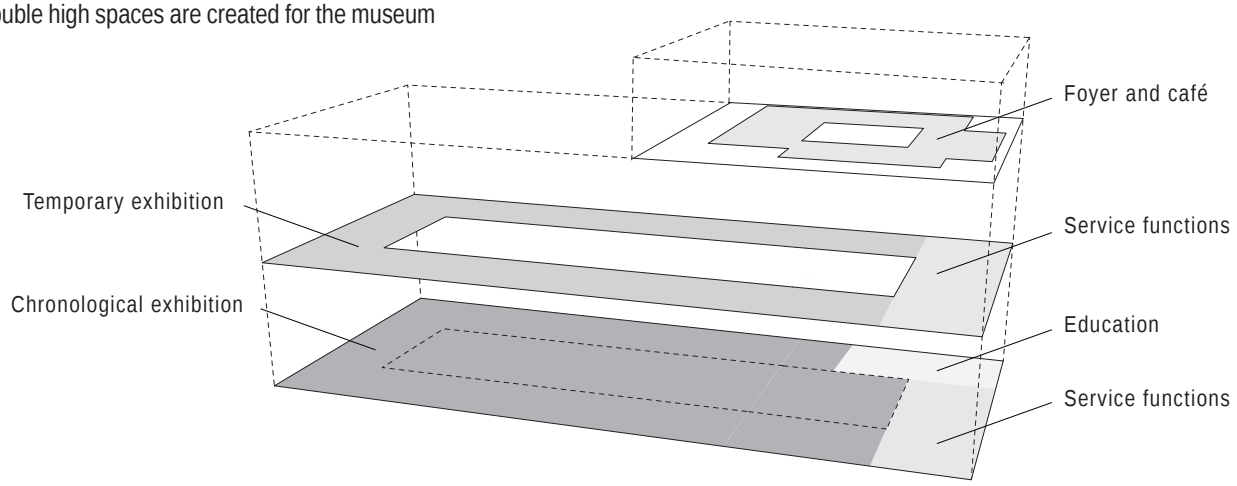




Detail 1:20

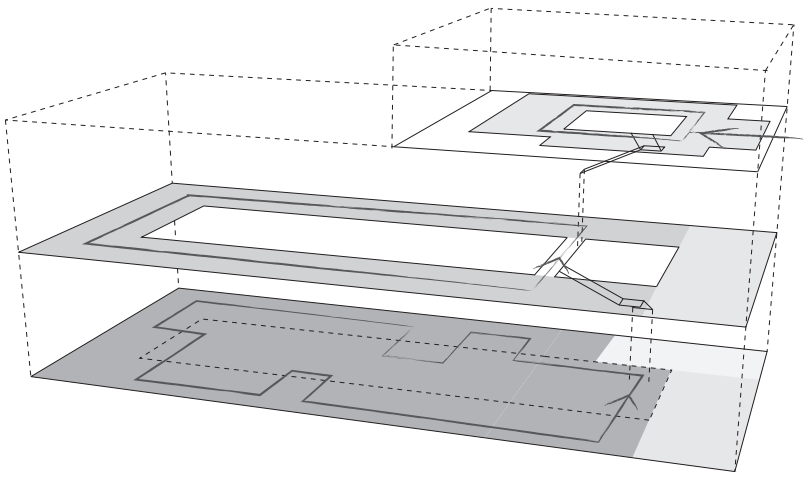
Underground spaces

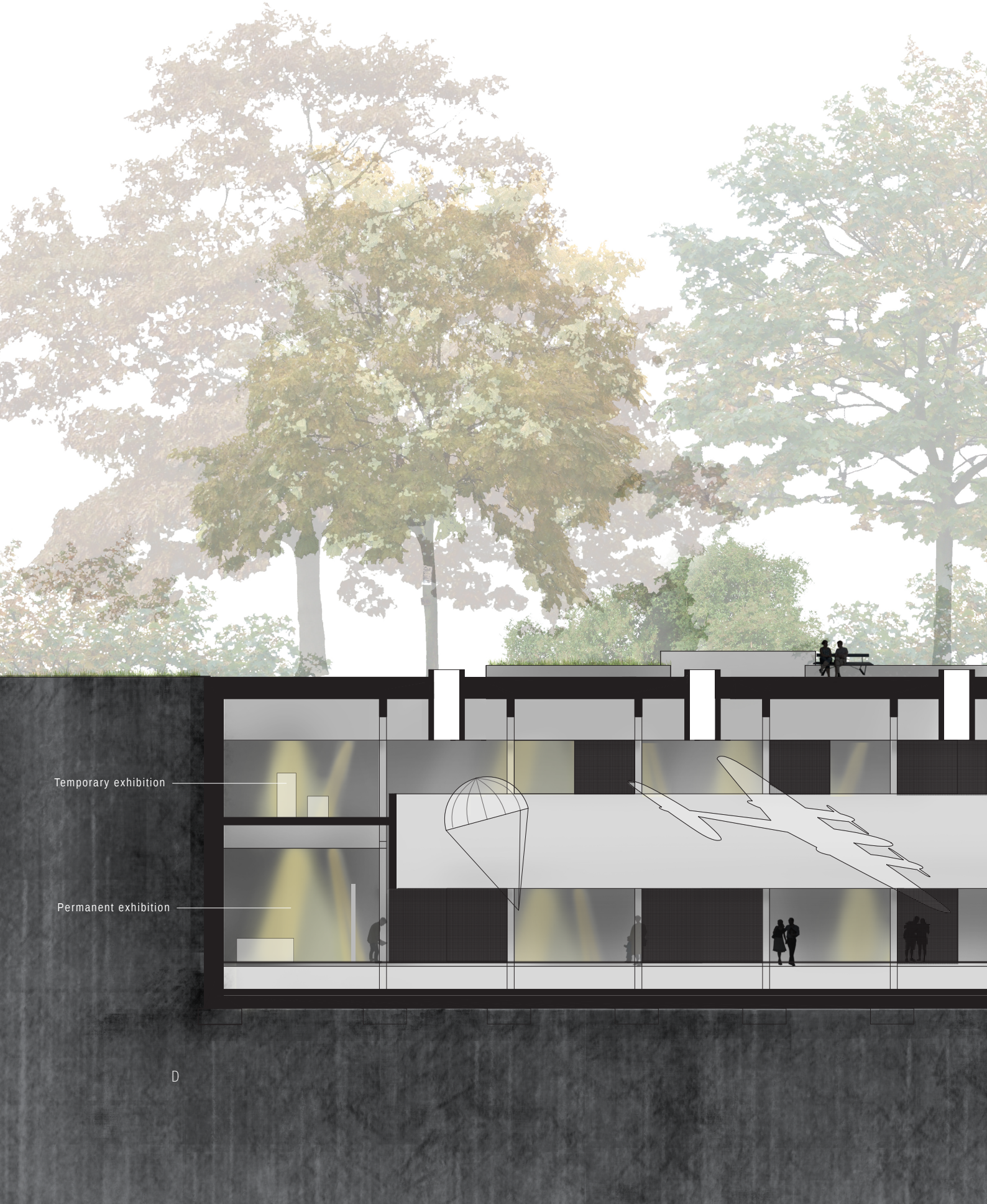
The exhibition and service functions are distributed on different levels in the building. The foyer and entrance areas are an open public space with relation to the park. It can be used independently of the exhibition spaces, which are located underground.
The two lower levels accommodate the temporary exhibitions on the -1st level and the permanent exhibition on -2nd level. Both single and double high spaces are created for the museum spaces.



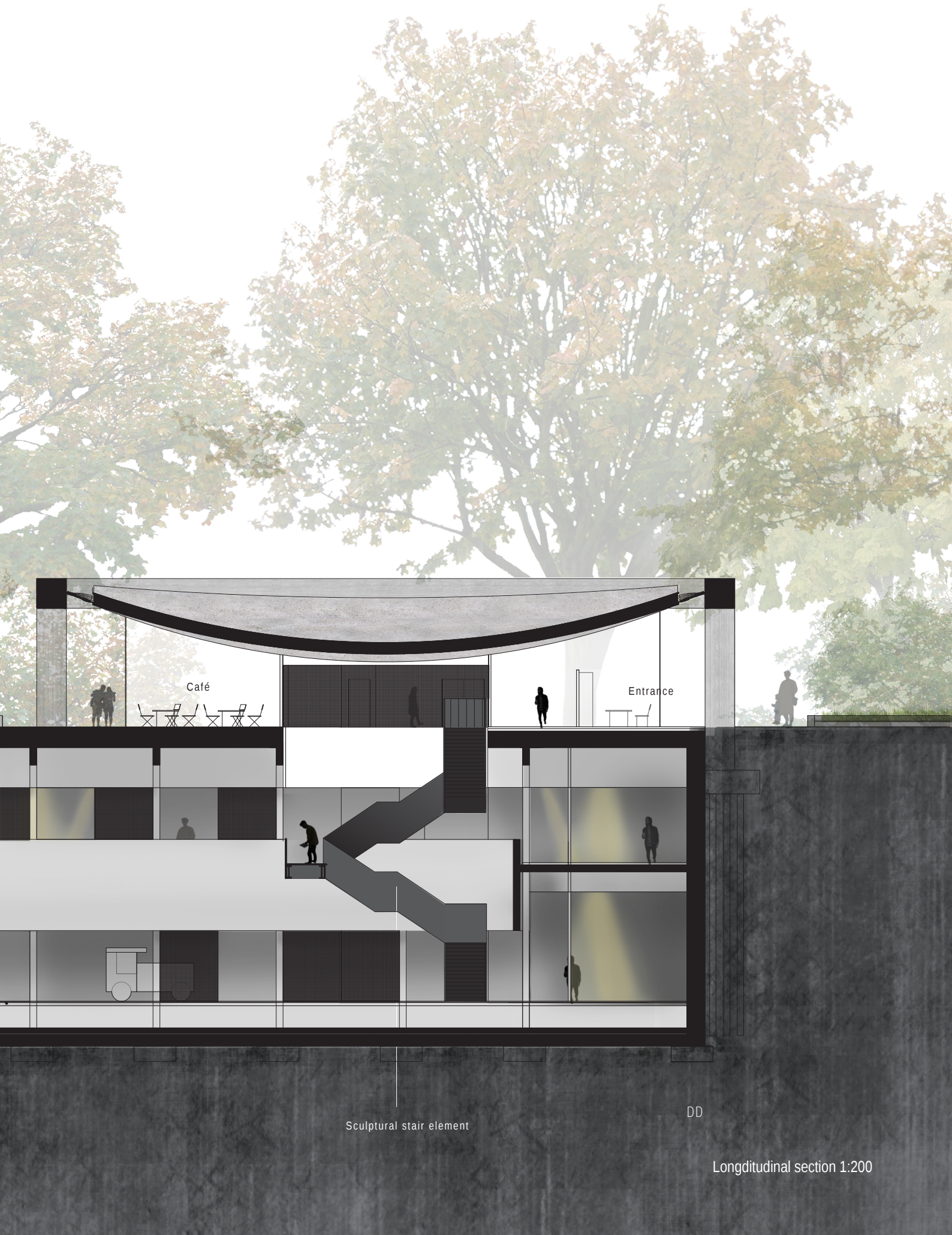
Flow

The circulation is structured around the vertical space connecting the levels. The two loops of the temporary and permanent exhibitions both connect to the stair and indicate a direction of the visit. The route of the temporary exhibition encircles the central space, while the - 2nd level allow the visitor to flow around between the low and higher spaces. The service functions are grouped on one side and don't interfere with the visitor flow.



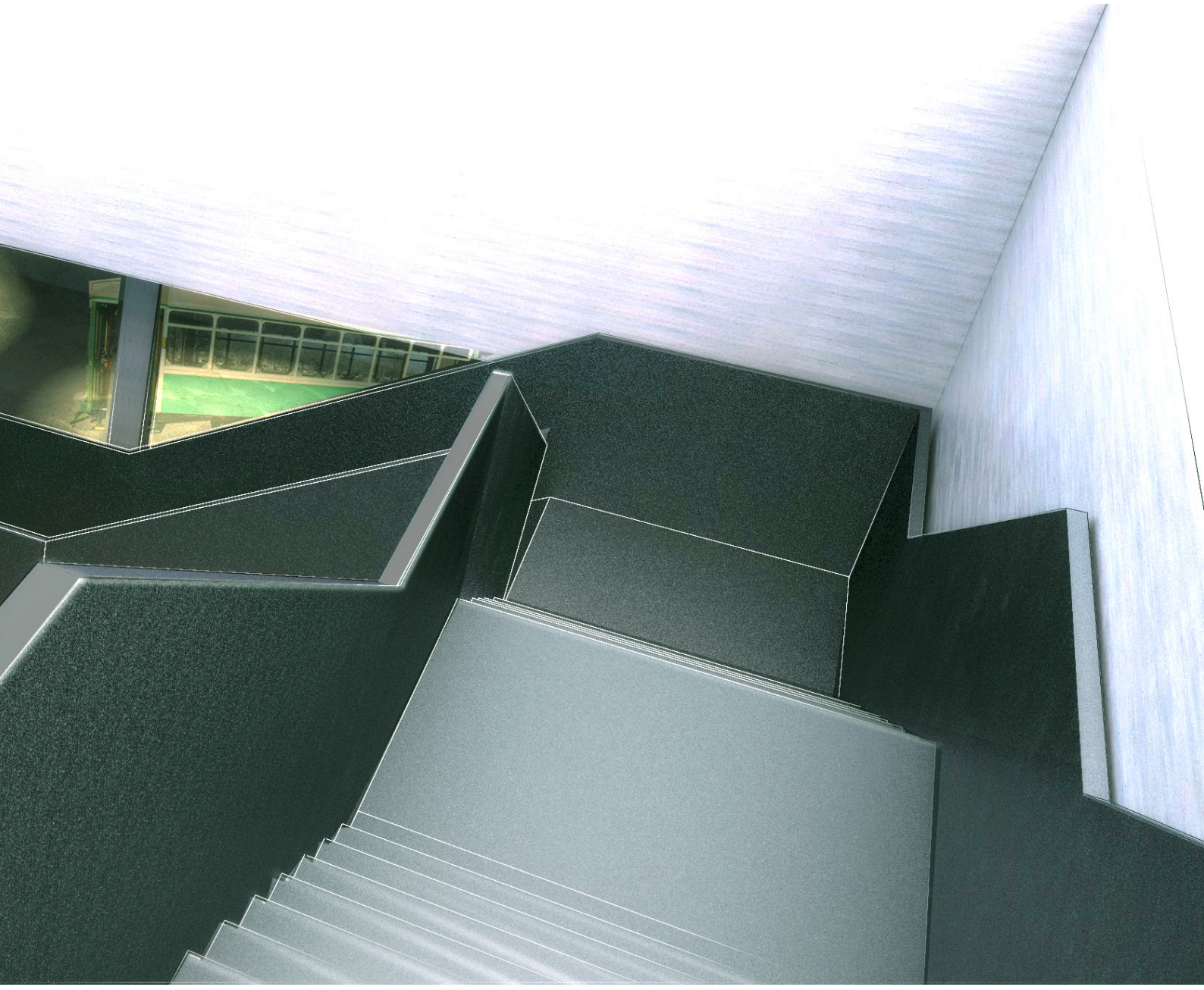


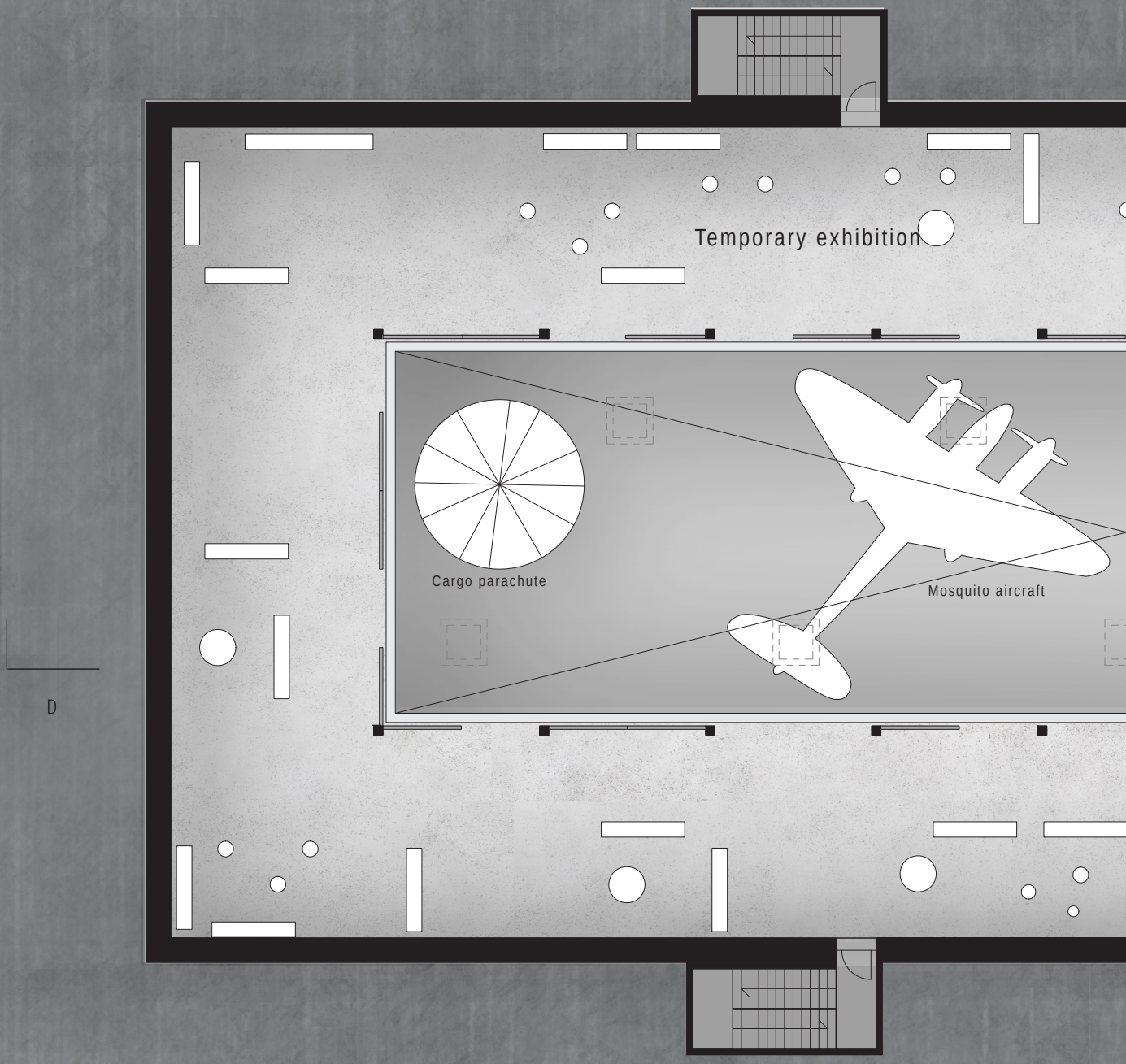
D

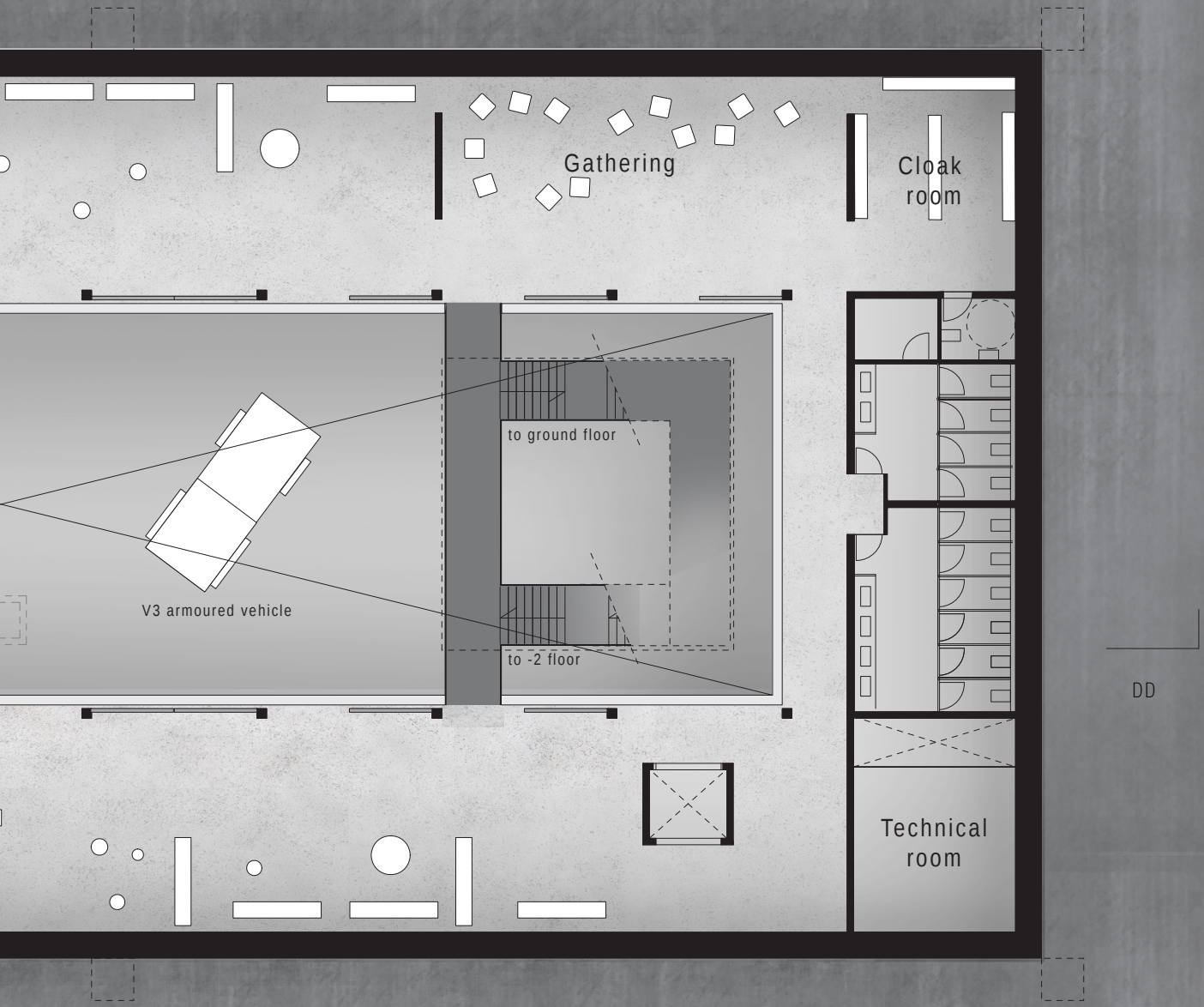


Longditudinal section 1:200

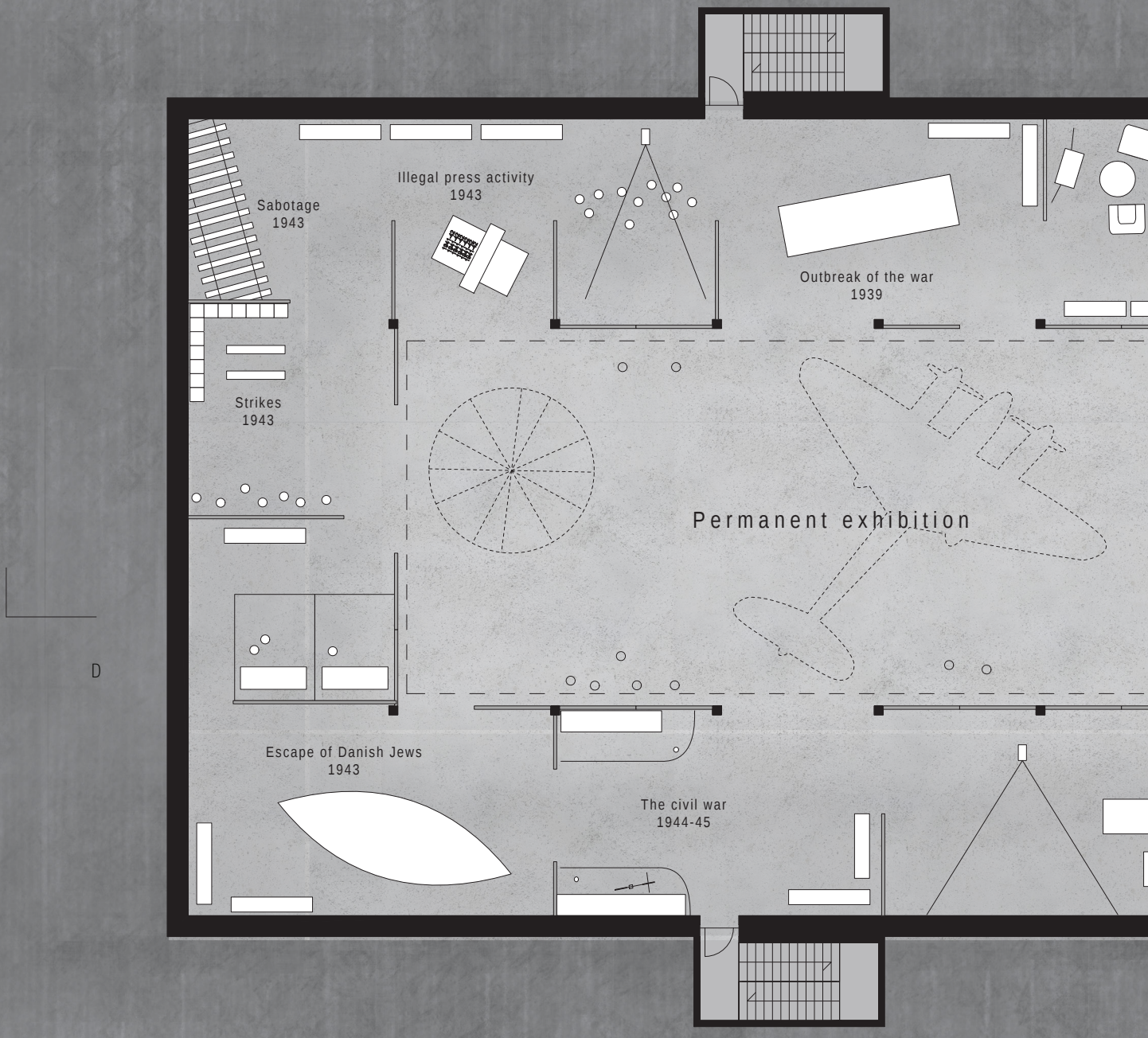

DANMARK FRIT



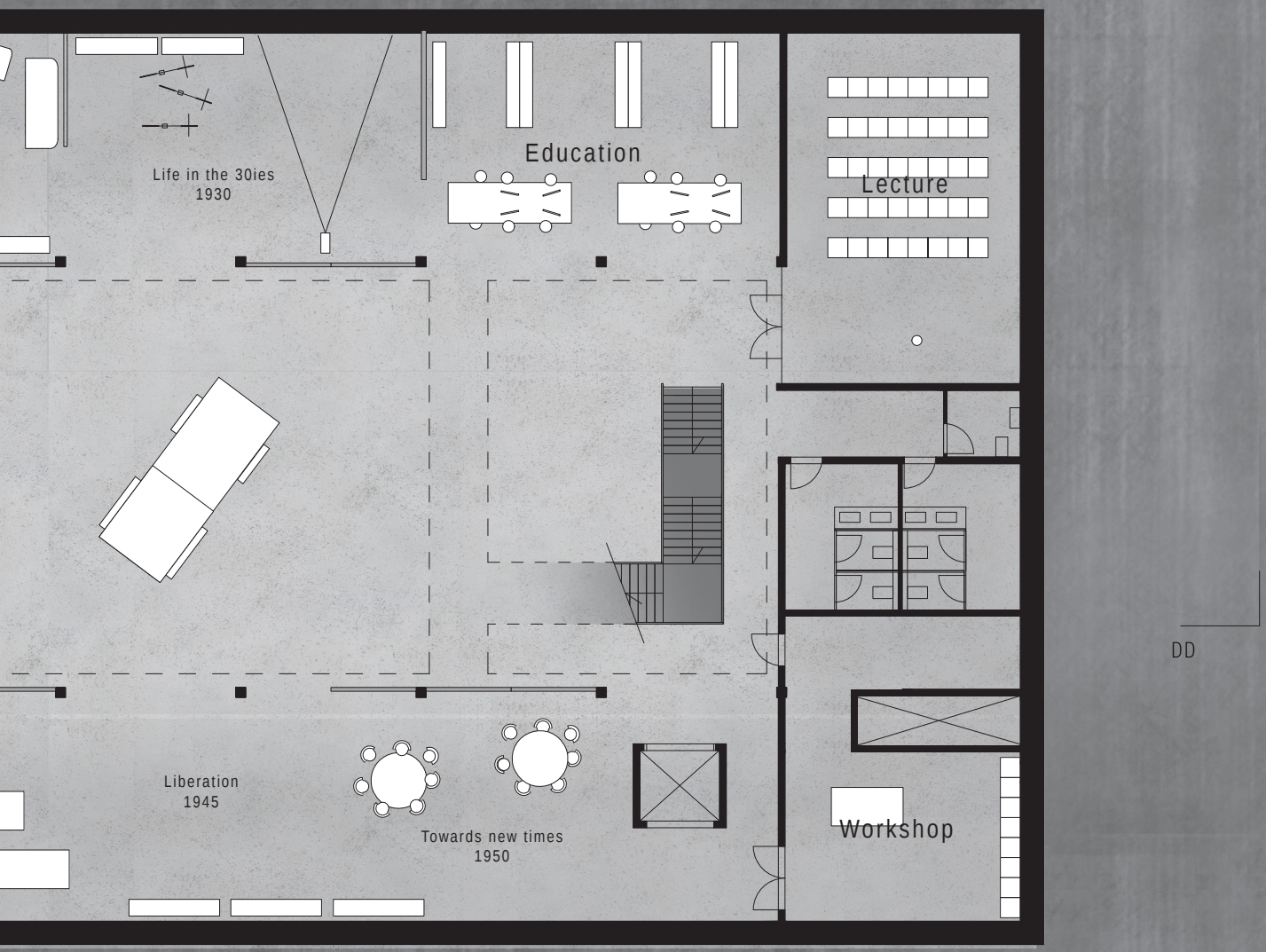

Temporary exhibition
Cargo parachute
Mosquito aircraft
D



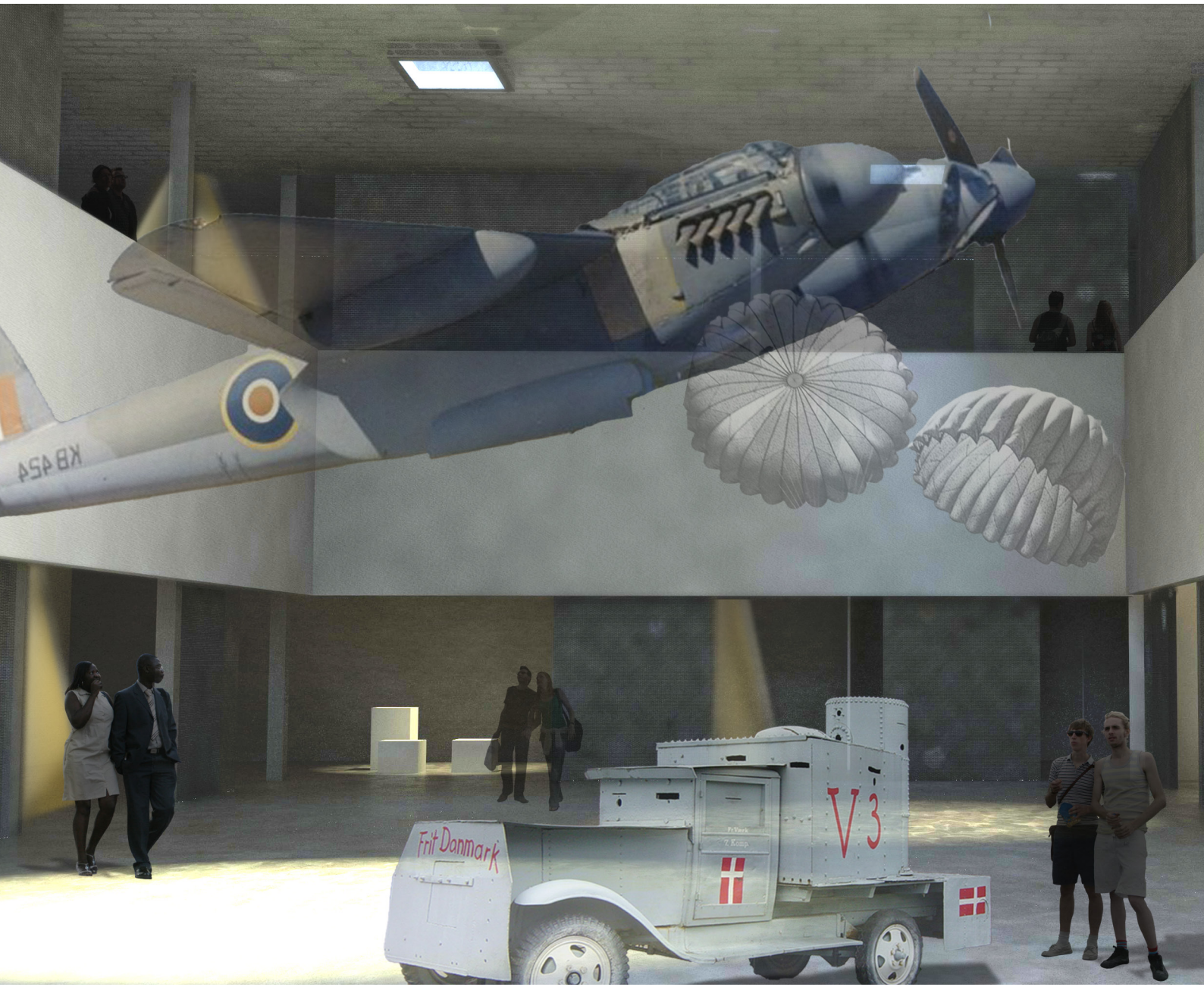
Basement plan, level -1 - 1:200


Sabotage
1943
Illegal press activity
1943
Outbreak of the war
1939
Strikes
1943
Permanent exhibition
Escape of Danish Jews
1943
The civil war
1944-45

D



Basement plan, level -2 - 1:200


Frit Danmark
V 3

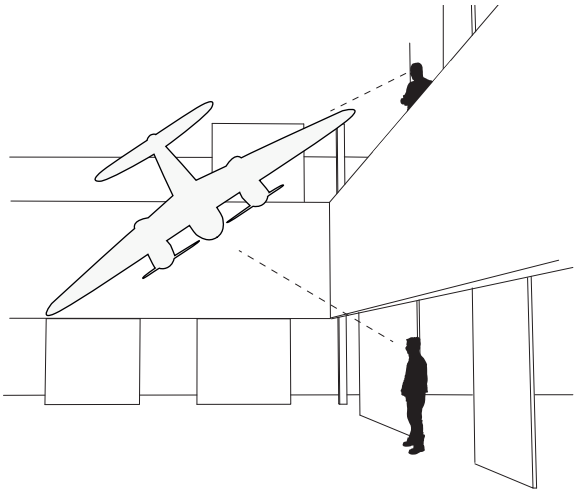
Exhibition

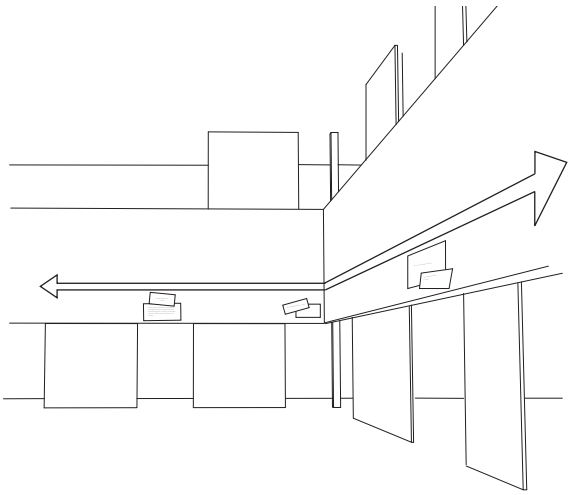
Visual connections link the exhibition spaces arranged in two levels. The flexible exhibition is placed in the upper level, with a flow around the balcony starting and ending at the steel bridge with the stair. The lower level is occupied by the permanent exhibition with the zones arranged in chronological along the periphery, but with a flow allowing to view them alternately with the main room.

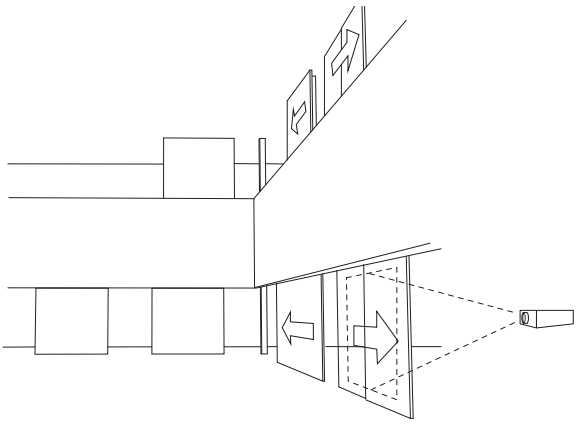
The two levels of exhibition allow to use the relations between the spaces actively as part of the display strategy. The levels allow to view the large artefacts from different angles and to experience them simultaneously with exhibition flow in the periphery.

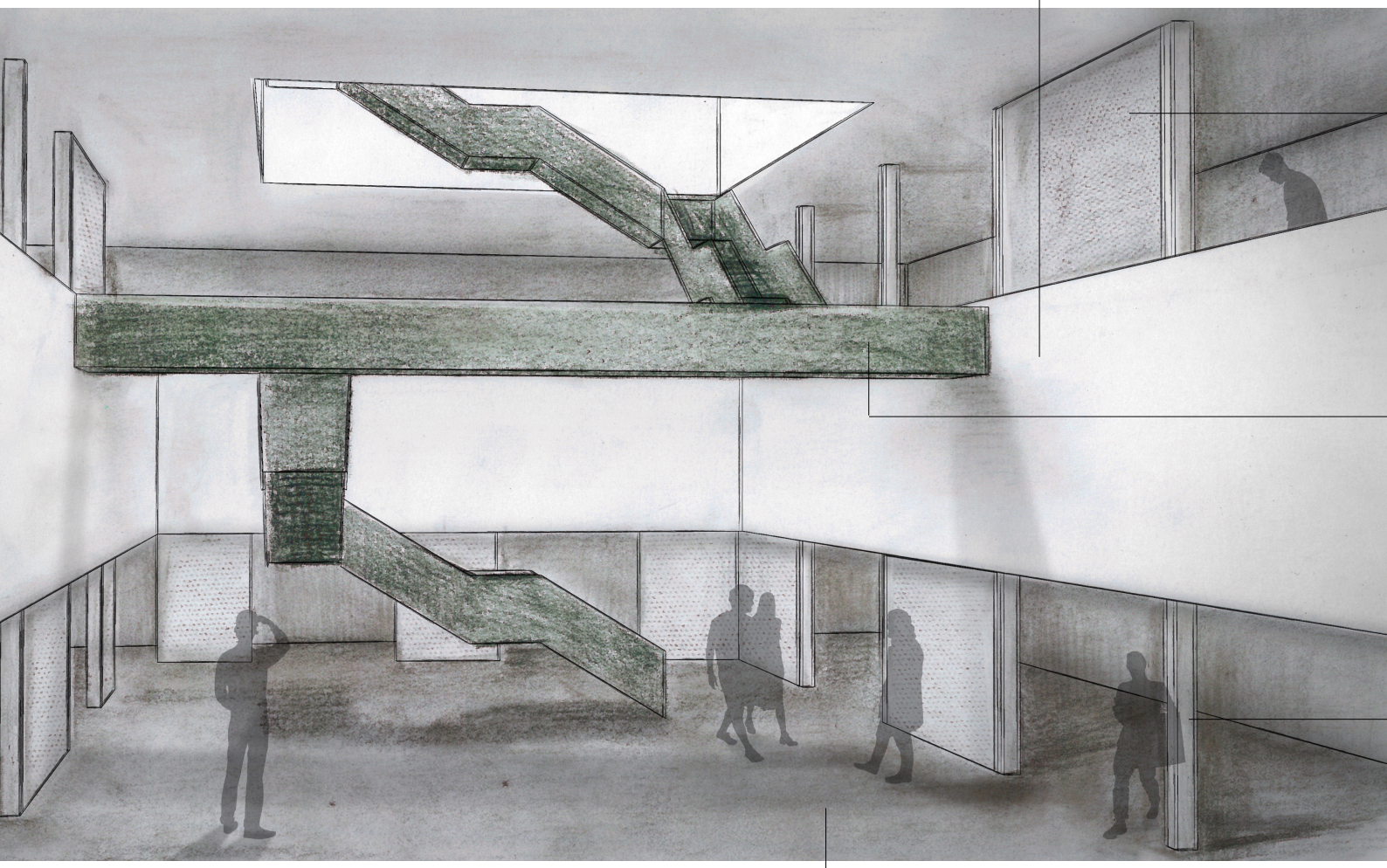
The horizontal ribbon wall element encircles the large exhibition space. Visually it works as a background surface for the hanging objects. It can as well function as a dissemination surface for projecting or display, for examples in the character of a timeline or introduction of the various zones in the permanent exhibition.

The bearing columns give a rhythm to the space and allow the light partition walls to be easily be moved around. They can be modified to adjust the enclosure and divisions of the single high exhibition spaces according to the needs, which will be especially relevant for the flexible exhibition on -1st level.

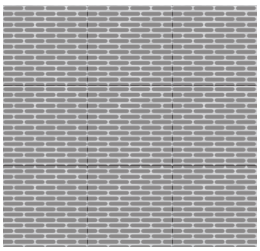




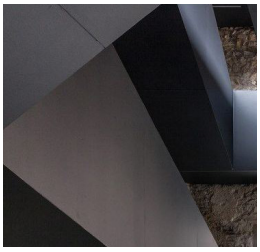




White stiated stucco



Perforated steel sheet



Matte painted steel plates

Exposed smooth concrete

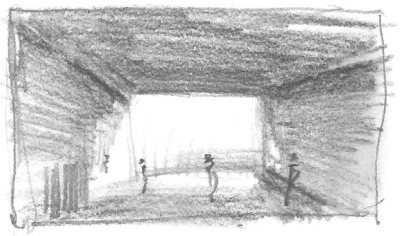
Grey stoneware floor tiles,
without grouts

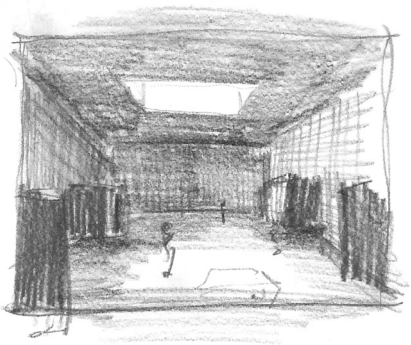
Materiality

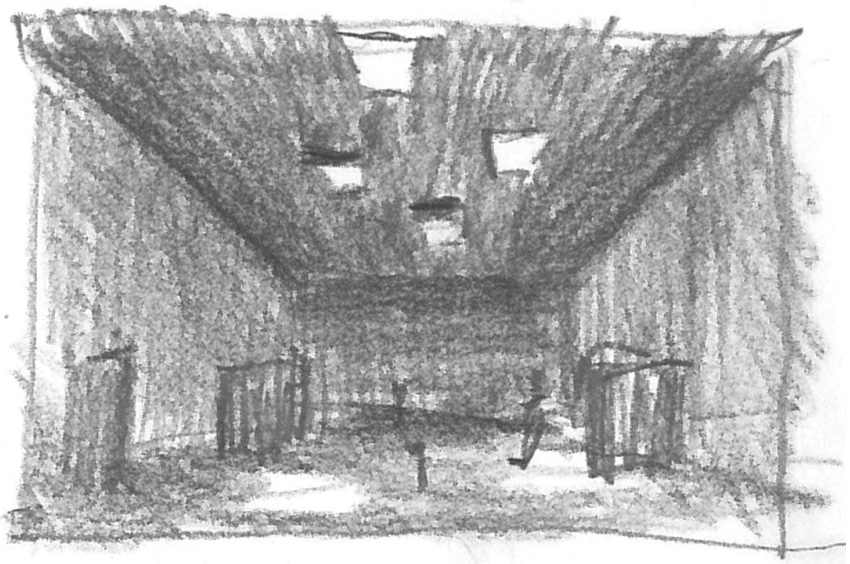
The material selection in the underground spaces is similar to the one in ground floor level. Steel and concrete are the two main materials, setting a rough and industrial appearance. The two elements of the ribbon railing element and the stair have more distinctive materials in colours contrasting each other. The black steel accentuates the facetted shape of the stair, enhancing its sculptural qualities. The ribbon wall surface is neutrally white to act as calm background surface. The partition walls have the perforated steel cladding towards the double high space, to distinguish them as flexible in contrast to the railing element. The space appears in neutral greytones to direct the focus on the exhibition

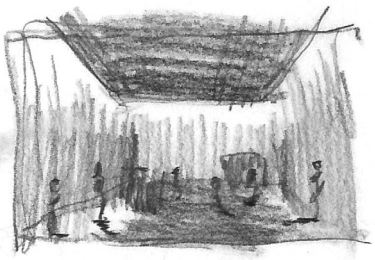
Skylights

The feeling of being underground is enhanced by the few light openings in the roof, as the thickness of the construction above is revealed. Few light spots are let in to add play in the interior. The contrast between the vast central space and the more confined niches in the periphery is accentuated. Only diffuse light can enter through the skylights and only used sparsely, as the exhibition spaces will primarily be lit up by artificial light settings.







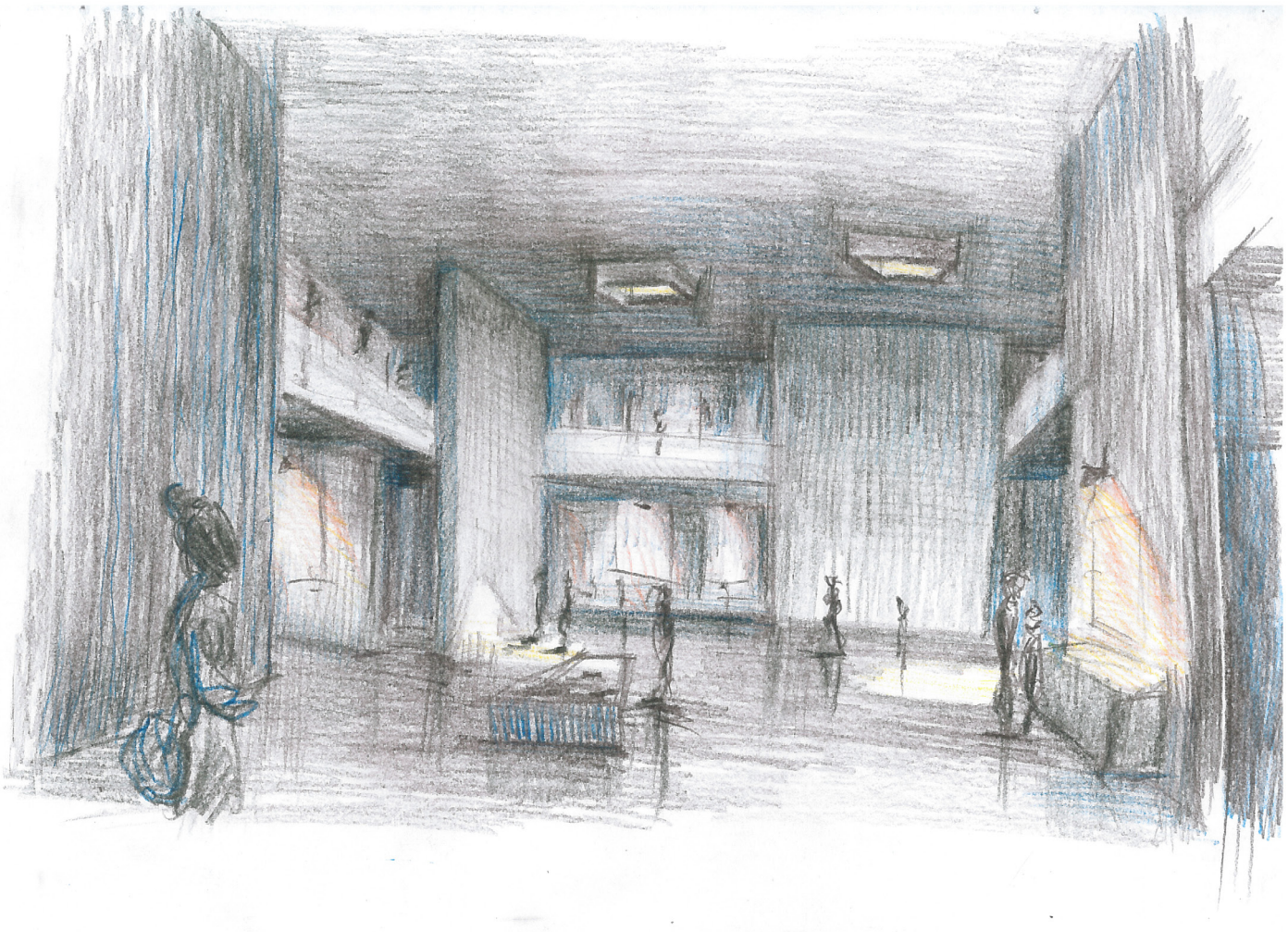


Conclusion

The new freedom museum houses the collections commemorating the resistance fight against the German occupation during WW2. It will become a cultural institution with a strong, recognizable image. Standing as a canopy among the green it invites for closer investigation and for a stay in the surrounding outdoor spaces around. It establishes a new public space for recreation and diversion out of everyday life, as well as an icon for the city. It is a place of knowledge propagation and storytelling on an intellectual but also an experiential level.

The architectural expression sets the mood for taking in stories of wartime and human struggles. By bringing the sensuous aspects into the museum experience through architecture, the visitor gets the chance to grasp the physicality and authenticity of the exhibit. The exhibition spaces guide the visitor through different layers of displays. Visual connections and spatial contrasts allow shifting relations between viewer and object.

The massive and heavy expression of the construction is the architectural interpretation of the museum's theme. The museum content is in this way the leading function that shapes the statement of the building. By uniting the atmospheric and the constructive idea, the hanging roof acts as the main architectural storyteller and a creator of identity.



Reflection

The project work has led to many reflections on museum design as well as on the approaches to architecture and engineering in general.

Neutrality or identity

Museum design requires a standpoint on the exhibition content and the concept of display. A distinctive design statement can create a strong experience and identity of the museum, but interfere with the exhibited content. An approach toward neutrality can direct the attention to the museums artefacts and context, but also result in indifference or characterlessness.
A museum is most often a building with a long span of lifetime and may therefore have needs for adaptations, changes and also a change in the interpretation of its content. Especially, when considering a historical museum, the perspective and interpretation of the past changes all the time. In the project many thoughts were invested in keeping the balance between offering a pronounced atmosphere and imposing a certain interpretation of the past. Notably, as the resistance fight till this day is a theme with controversies and ongoing discussion, also relating to today's issues of politics and handling conflict situations around the world. If the massivity and the hanging roof are excessive or suitable can be discussed. The idea though comes from a concious choice to establish a readable identity of war-time museum.

Exhibition design

Museums are undergoing a development towards commercialization on one hand and their educational role on the other. They have to compete with other knowledge dissemination platforms. Going back to the essence of a museum – the meeting with the authentic artefact – is what gives the significance of the museum as place. The exhibition is therefore central to the whole museum endavour. In the process of designing many questions were left unanswered about how the exhibition content would be displayed. A space with little spatial intervention leaves the exhibition rooms flexible with a tabula rasa for the curators. However, spatial sequencing, visual connections and lighting can enhance and support the wished experience. Ideally, the process would be a collaboration. The building and exhibition would be designed together, with a fluid border between the exhibition and building concept, thus creating a total experience for the visitor. By assuming and guessing, a solution was found for the project, leaving option for adaption the exhibition in many ways, and still having a clear architectural statement. The point of departure was the structuring as a chronological and temporary exhibition space and the presentation of the big artefacts. The fact of building underground focuses the attention on succession of spaces, the movement between them, as other contextual aspects are not present and the space is by its' nature introvert.

Monumentality or humbleness

Another polemic, which was present during the design process was the issue of how the architectural piece is present in its context.
Landmark buildings make the city readable; they present a statement of importance. Urban spaces often benefit from buildings with a clear character and a strong presence. The building concept, starting from the initial thoughts, set out a direction of a marked building with a strong roof element as the leading motive. The position taken, to create an object with monumental character, can be discussed in line with the general polemic if an architectural piece should blend in with the context or break with it. However, an opposite approach than the one taken, would focus on the near surroundings, paying more attention to the park and the grown environment. A more respectful and humble typology might blend in with the context and create a more informal atmosphere. Contextuality is however not only a question of humbleness, but a certain interpretation of the surrounding. The monumental building places itself among the other distinctive edifices in the surroundings, saturated with historical traces and signs of military and civil power, where the museum situated itself as another element in this composition.

Integrated design

The design has achieved a high degree of integration of technical and artistic aspects. In fact, the artistic vision of the roof and foyer space is totally dependent on the constructive solution. The previosly described tectonic approach implied a constructive honesty, which quite early in the process eliminated other structural systems than a hanging cable structure. That concept informed many other design choices about organisation, plan solution, materials aso, and was in that way very governing. The engeneering knowledge was used on a very conceptual level from the very beginning. Later on in the process it came in more and more specific to detail the chosen concept and make it buildable. In fact, the measures taken to improve the technical aspects, such as the cable sag, the big frame dimensions, visible anchoring of the cables, all enhanced the aesthetic choice springing from the atmospheric concept. The proces was therefore not an optimization of the design to live up to a set of technical criteria, but a concretization of a given design idea that already contained physical and poetic elements.

Appendix

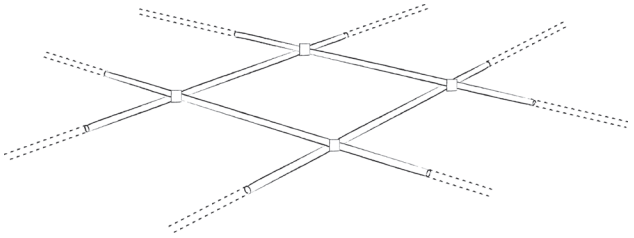
Drawing folder:

1 - Siteplan 1-500
2 - Ground floor 1-100
3 - -1st floor 1-100
4 - -2nd floor 1-100
5 - Section A 1-100
6 - Section B 1-100
7 - Elevations 1-200
8 - Detail 1 1-10
9 - Detail 2 1-5
10 - Detail 3 1-20
11 - Mechanical ventilation diagram

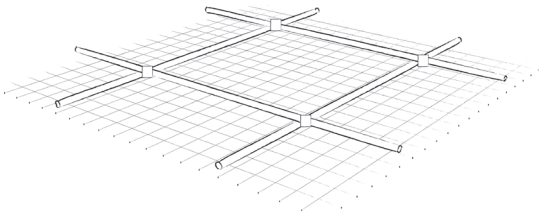
1 Construction

1.1 Roof layers

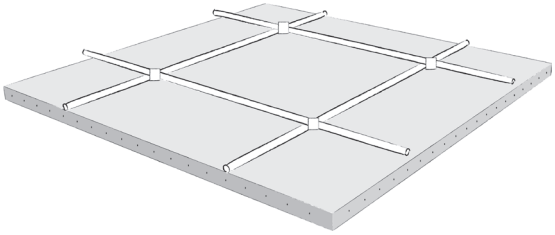
The roof structure itself consists of several layers creating a sandwich structure of concrete coating on rigid insulation. The weight of the roof layers rests on the main cables, by attachment of the lower concrete layer.



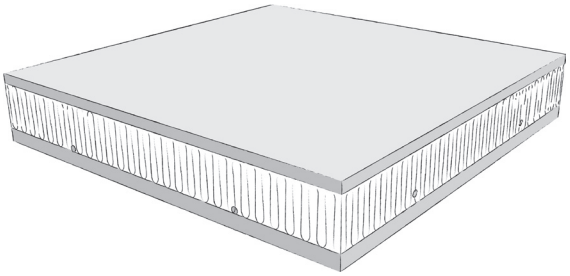
The main bearing elements of the roof are the cables, 3cm thick, with 1m spacing, hanging in two directions. One direction of cables is placed “above” the other. In each intersection point the cables are joined together



A steel net with finer spacing, 100x100, is suspended under the main cable structure, to create a skeleton for a layer of shotcrete.



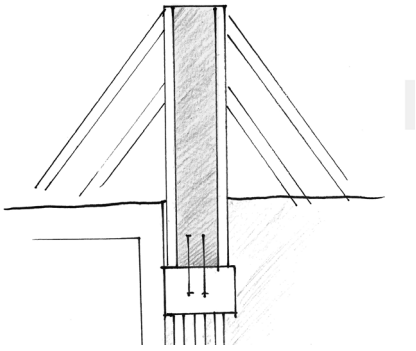
The concrete layer is sprayed on and trowelled for a smooth surface. It is not bearing, but provides interior finish. The cables are in this way not cast inside the concrete, and small movements of them are then allowed to avoid cracking of the concrete.



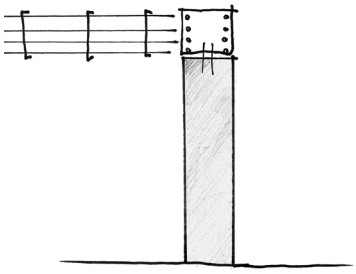
On top of the bottom concrete slab, a layer of pressure resistant insulation is laid. The exterior of the roof is protected by another spay concrete layer on top of the insulation.

1.2 Construction method

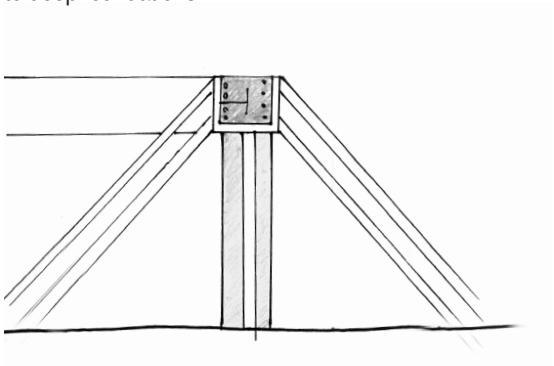
In the following, an idea of is shown of how the pavillion structure would come into place.



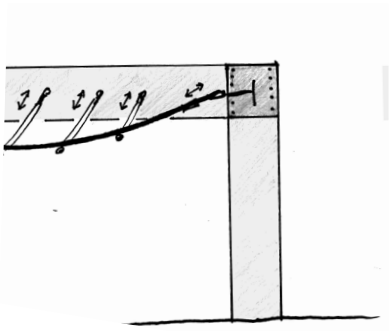
After finishing the underground section, the columns are cast, attached to deep foundations.



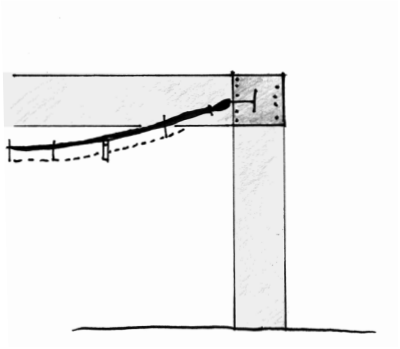
Reinforcement bars for the frame are connected together, with special care in the corners.



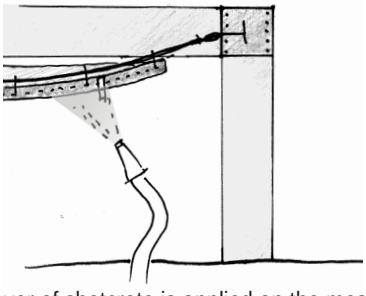
The edge frame is cast in place as one piece.



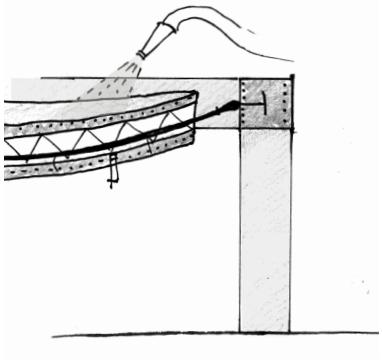
The cables are hung on the anchors cast into the frame. Their lengths are adjusted to align the two directions of cables to form a base for the roof surface.



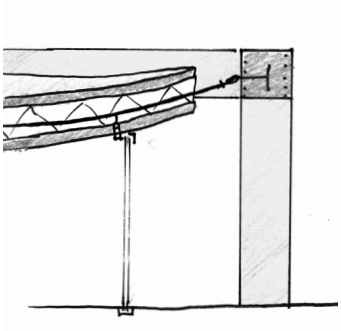
A finer mesh is mounted on the cables, as well as all elements going to interrupt the later applied layer of concrete fx. the facade mountings (det. p. 86).



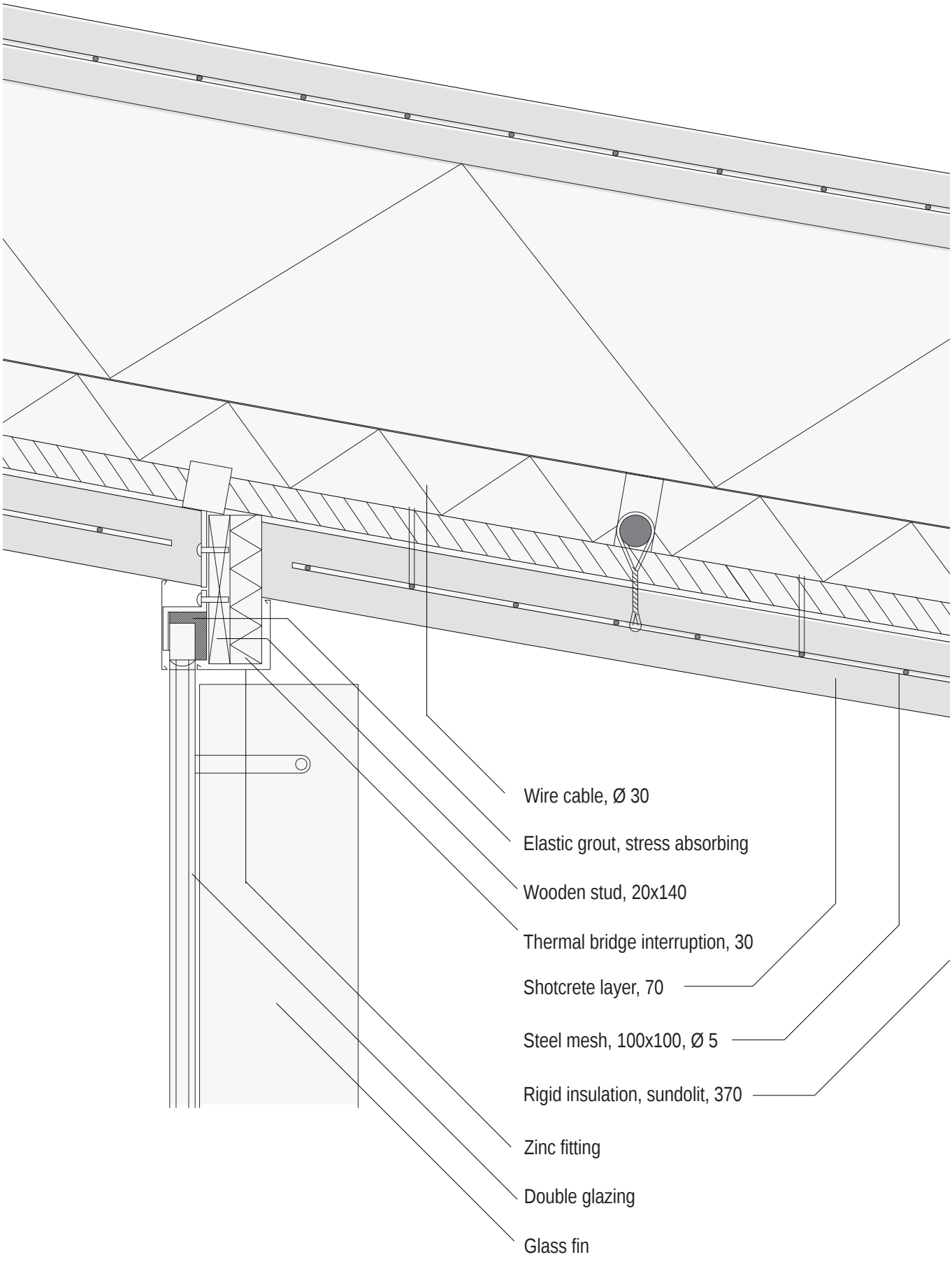
Interior layer of shotcrete is applied on the mesh.



Insulation layer and the top concrete layer is applied.



The facade glazed panels are mounted and the interior finished off.


Wire cable, Ø 30
Elastic grout, stress absorbing
Wooden stud, 20x140
Thermal bridge interruption, 30
Shotcrete layer, 70
Steel mesh, 100x100, Ø 5
Rigid insulation, sundolit, 370
Zinc fitting
Double glazing
Glass fin

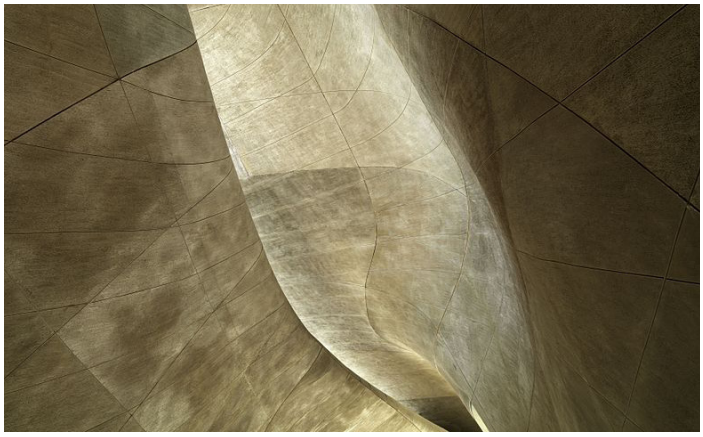
Detail 1:5

1.3 Shotcrete

The shotcrete technology allows to cast concrete without a formwork giving a great design freedom.The concrete is spayed directly on the construction in many layers and then the finish surface is shaped with f.x with a trowel.

Museum of Jewish History in Warsaw is an example of excelent shotcrete work. The walls are mounted on a steel sceleton and sprayed on a reinforcement net in a layer between 50 and 160 mm thick. The big surface (26 m heigh) requires diletation joints, also utilized as guides to control the surface geometry. The joints are also used aesthetically to visually enhance its curvatures of the wall. (Shotcrete. 2015)

The Freedom Museums' roof is not that extensive, but similarily all elements interupting the concrete surface will have to be installed beforehand (step 5, p.81). Using shotcrete is in our case a cost- and labour effective way to create the double curved shape, avoiding to need of a complex formwork.

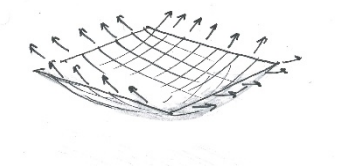


2 Statics

The bearing structure is built of reinforced concrete, with suspended roof. The interior is enclosed by a light, self-bearing glass façade. The roof structure consists of steel cables carrying a thin concrete shell. Anchored in massive beams along the edge, the roof surface spans in two directions, creating a convex shape towards the interior. The edge frame rests on the four columns in the corners.

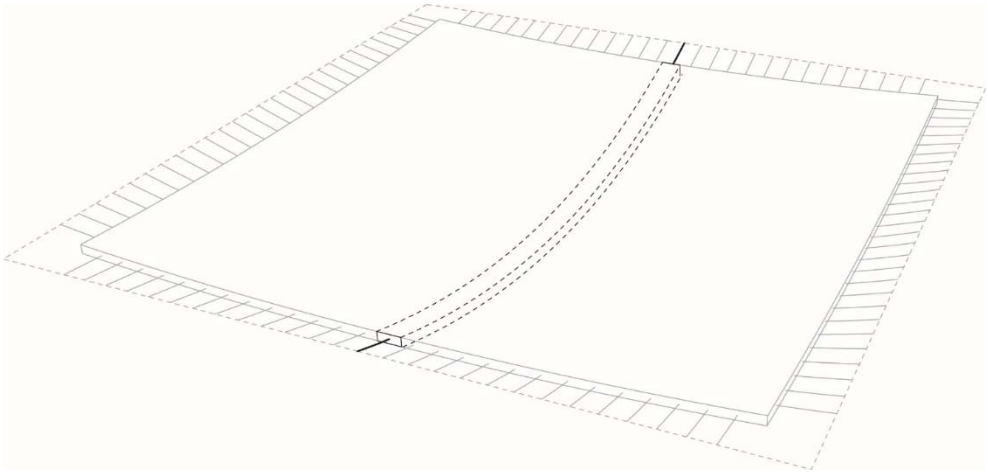
The structural analysis will focus on the pavilion structure on ground floor level with the hanging roof to show that the design is feasible. The roof and frame are meant to have a heavy expression, why over dimensioned structural members are accepted. The beam cross section is verified separately regarding the bending moment from horizontal and vertical forces. The deflection in the horizontal direction is checked, and finally the column is shown to have a sufficient bearing capacity

2.1 Loads and assumptions



2.1.1 Cable mass

A **strip of the roof of 1m** is considered, to find the loads and magnitude of the tension in the cables. The cables are only subjected to gravitational force and their **tension depends on the cable weight and the sag** in the middle (see 1.3). The construction weight together with the snow load, are expressed **as mass of the cable pr. m**. to then find the magnitude of the tension.



Loads:

Cable wire:
$r = 15\ mm$
$\rho_s = 8050\ kg/m^3$
$g_{cable} = 5{,}69\ kg/m$

Concrete shell:
$t = 140\ mm$
$\rho_c = 2300\ kg/m^3$
$g_{concrete} = 322{,}00\ kg/m$

Insulation:
$t = 350\ mm$
$\rho_{iso} = 23\ kg/m^3$
$g_{iso} = 8{,}05\ kg/m$

Snow load:
$q_{snow} = 0{,}72\ kN/m^2 = 0{,}72\ kN/m^2 * 101{,}97\ kg/kN = 73{,}42\ kg/m$

2.1.2 Load combinations:

By applying the load combination factors to the weight, the cable tension corresponds to the loading of the beam in ULS and SLS.

The loads are carried by two layers of cables in perpendicular directions, therefore the weight applied is **divided by two**, to take the **double span** into account.

ULS:

$P_d = 1{,}0 * K_{fi} * g + 1{,}5 * K_{fi} * q$, *where* $K_{fi} = 1{,}1$ (CC3) ((Jensen, 2011, p . 163)

$P_d = (g_{cable} + g_{concrete} + g_{iso}) * 1{,}1 + (1{,}5 * 1{,}1 * q_{snow,\ doubled})$ $kg/m = (5{,}69 + 322{,}00 + 8{,}05) * 1{,}1 + (1{,}5 * 1{,}1 * 73{,}42)$ $kg/m = 490{,}46\ kg/m$

$P_d = 490{,}46 / 2 = \underline{245{,}23\ kg/m}$

SLS:

$P = 1{,}0 * K_{fi} * g + 1{,}0 * K_{fi} * q$, *where* $K_{fi} = 1{,}1$ (CC3) ((Jensen, 2011, referred to as "TS", p . 163)

$P = (g_{cable} + g_{concrete} + g_{iso}) * 1{,}1 + (1{,}1 * q_{snow,\ doubled})$ $kg/m = ((5{,}69 + 322{,}00 + 8{,}05 + 73{,}42) * 1{,}1)\ kg/m = 450{,}08\ kg/m$

$P = 450{,}08 / 2 = 225{,}04\ \underline{kg/m}$

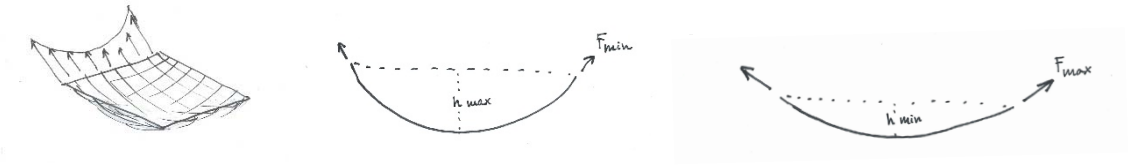
1.3 Cable tension

The loaded cable treated as a parabolic curve, and the tension is found according to:

$$T_{max} = \frac{\omega * L}{2} * \sqrt{1 + (\frac{L}{4h})^2},\ where\ \omega = \frac{m\ [kg/m]}{2} * 9{,}81[m/s^2]$$

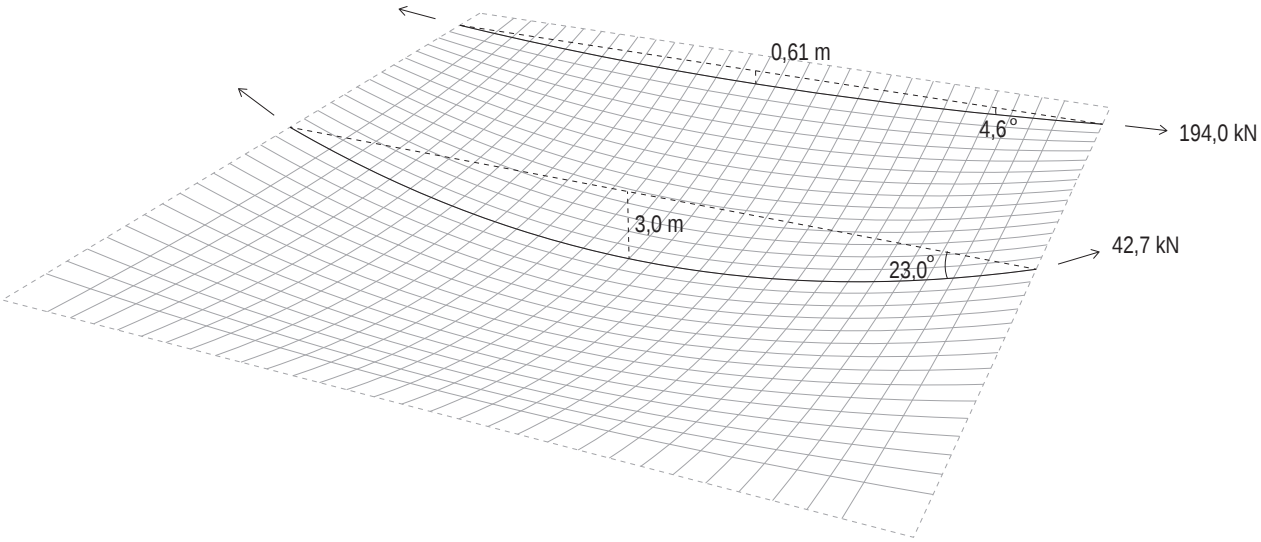
where:

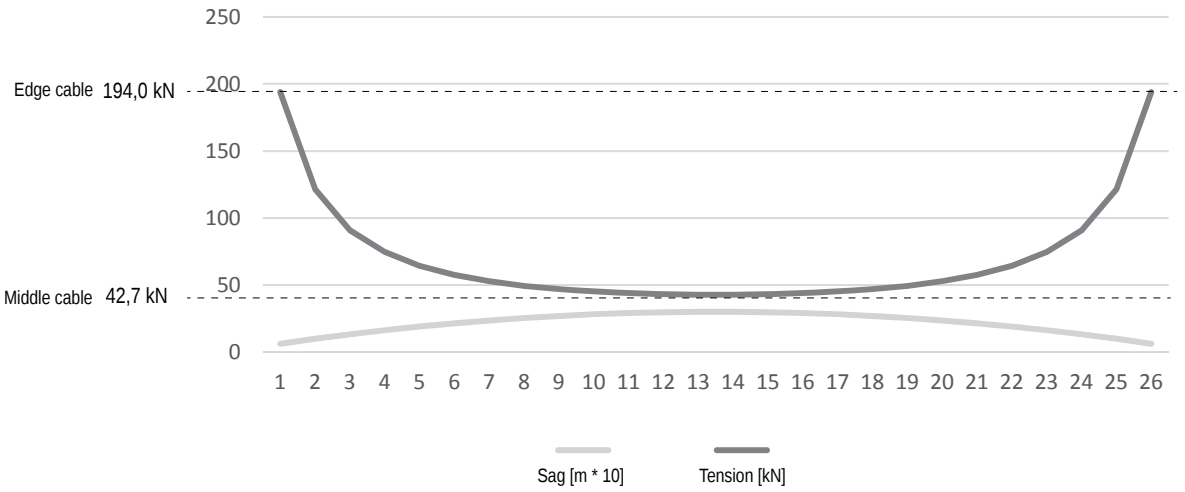
L is the horizontal distance between the endpoints
h is the sag, measured vertically
m
(based on Meriam Craige s.298, prob 5/17) (Meriam, 2013)

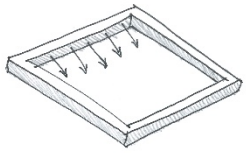


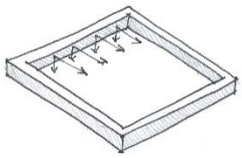
2.1.3. Variation in the cable tension

As seen on the illustration below, the **angle of the cables varies** along the length of the beam. So does the load applied by the tension of the cable. The middle cables, with a greater sag, are not as tense as the ones in the sides. As seen, the connection between the sag and tension is non-linear, the middle cables drag many times less than the outermost ones. To avoid a complex calculation with a varying load, **the load is simplified** and will be assumed to be **uniformly distributed** along the beam.









2.1.4 Horizontal and vertical force

The beam cross section is being checked in **horizontal and vertical direction independently**. The fact that the cables affect the beam with an angle, and would cause an uneven stress distribution across the cross section, is disregarded. The forces from the cables are split into the **horizontal and vertical components**, acting perpendicular to the cross section.

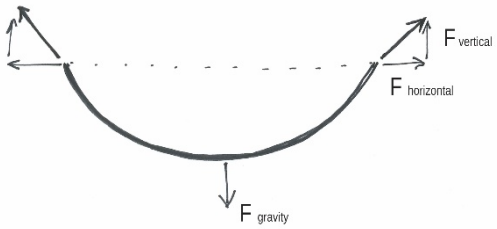
For the horizontal loading, **the edge cable contributes with the greatest force** in horizontal direction. To be on the safe side, the biggest forces from the edge cables are applied on the whole length of the beam of **193,3 kN/m.**

For the vertical loading the contributions are close to constant, as they correspond to the **self-weight of the cables**, as:

$F_{gravity} - F_{vert} - F_{vert} = 0$

The variation of F_{vert} (in Tab 1) is due to the fact that the length, and therefore the mass, of the cables varies slightly. For the vertical loading of the beam the load of **16,7 kN/m** is considered, plus the self-weight of the beam, 38,1 kN/m.

FBD of cable



Tab. 1

	Nr		Sag [m]	Length [m]	Tmax [kN]	Angle [deg]	F vert [kN]	F horz [kN]
Edge cable	1	6,1	0,61	28,03	194,0	4,6	15,7	193,3
	2	9,8	0,98	28,09	121,5	7,5	15,7	120,4
	3	13,2	1,32	28,16	90,9	10,1	15,9	89,5
	4	16,2	1,62	28,24	74,7	12,4	16,1	72,9
	5	19	1,9	28,33	64,3	14,7	16,3	62,2
	6	21,4	2,14	28,43	57,6	16,4	16,3	55,2
	7	23,6	2,36	28,51	52,7	18,1	16,3	50,1
	8	25,4	2,54	28,6	49,4	19,6	16,5	46,5
	9	26,9	2,69	28,67	46,9	20,6	16,5	43,9
	10	28,1	2,81	28,73	45,2	21,6	16,6	42,0
	11	29,1	2,91	28,78	43,9	22,2	16,6	40,6
	12	29,7	2,97	28,81	43,1	22,7	16,7	39,8
Middle cable	13	30	3	28,83	42,7	23,0	16,7	39,4

2.2 Cable cross section - ULS

The cables are assumed to be solid, of steel S550. The check if the chosen **cable diameter is sufficient** to resist the worst case of the tension in the cable, the stress in the cross section is compared with the design yield strength of the steel.

$f_{ck} = 550\ Mpa,\ f_{yd} = \frac{f_{yk}}{\gamma_s} = \frac{550}{1,2} = 458,33\ Mpa$

$r = 15\ mm$

$A = 706,5\ mm^2$

$F_{max} = 193,3\ kN$

$\sigma = \frac{F}{A} = 273,6\ Mpa < 458,33\ Mpa$

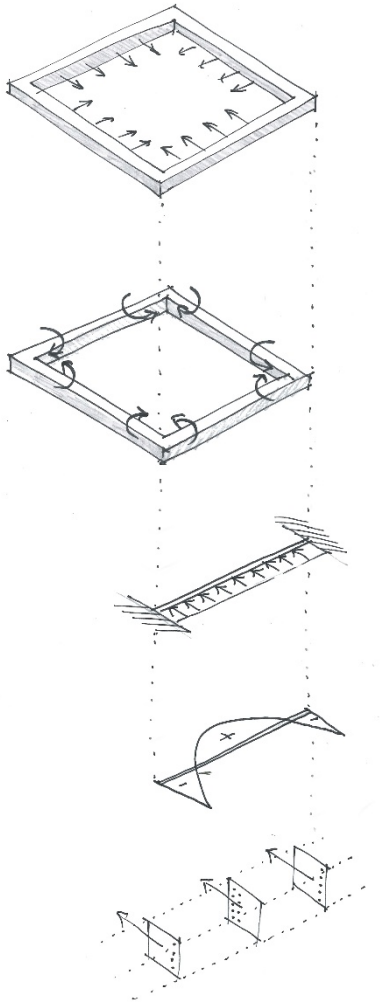
$\sigma_s < f_{yd}$

As the stress is lower than the steel strength, the cross section of the cable is concluded to be suitable.

2.3 Beam cross section - ULS

2.3.1. Horizontal loading

The precondition for the edge frame to work is, that the corner connections are able to transfer moments between the beams. Since all four beams are loaded by the cables, the moments work in opposite clock directions and counterbalance each other. Each beam, when considered one at a time, is therefore **fixed on both ends**. By this, the maximal bending moments are smaller than they would be in a simply supported beam. This principle sets very high requirements for the **corner joints**, as they are subjected to large forces "ripping" them apart.



The beam can now be treated as a member with fixed supports and with a uniform distributed load. Hence, the bending moments are:

At **the ends**:

$$M_{ed} = \frac{1}{12} * q * L^2 = \frac{1}{12} * 1693{,}3\ kN/m * (30{,}6m)^2 = 15.083\ kNm$$

In **the middle**:

$$M_{ed} = \frac{1}{24} * q * L^2 = \frac{1}{24} * 193{,}3\ kN/m * (30{,}6\ m)^2 = 7.542\ kNm$$

(Madsen 2011, p. 344)

In the following the cross section's bearing capacity is verified. The reinforcement is considered **separately for each force**, so the cross sections are considered as if with tensile reinforcement only. It is a rough approximation, as in the actual beam the bars would be all contributing to the cross section stiffness in each part of the beam. Fx. the bars on one side may work as tensile reinforcement in the middle, but as compressive reinforcement at the nodes.

	Material data	(Jensen,2008)
C40		
f_{ck}	40	Mpa
f_{cd}	28,6	Mpa
γ_c	1,45	
S550		
f_{yk}	550	Mpa
f_{yd}	458,33	Mpa
γ_s	1,2	
ε_{cu3}	0,35	for f_{ck}<50 Mpa
ε_{yd}	0,23	
ε_{uk}	5,0	
Constants		
η	1,0	for f_{ck}<50Mpa
λ	0,8	for f_{ck}<50Mpa

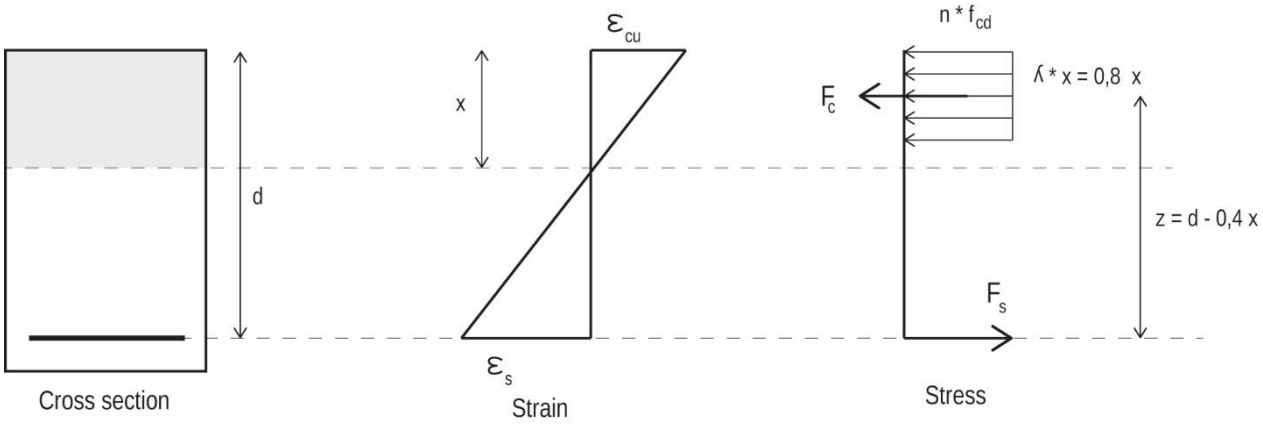
Bearing capacity for negative moment reinforcement:

b = 1300 mm, h = 1300 mm,

d = 1130 mm

51 pieces of r = 16 mm, in 3 layers

$A_s = 40995{,}8\ mm^2$



The height of the **neutral line, x,** is found.

The equilibrium of horizontal forces gives (Jensen, 2008 p. 105-108):

$F_c = F_s$

$0{,}8\ x * n * f_{cd} * b = A_s * f_{yd}$

$x = 1{,}25 * (A_s * f_{yd}) / (b * f_{cd}) = \underline{632{,}3\ mm}$

The **breaking moment M_{rd}**.

The inner moment around the reinforcement is (Jensen, 2008 p. 105-108):

$M = F_s * z$

$M = A_s * f_{yd} * (d - 0{,}4\ x)$

$M_{Rd} = A_s * f_{yd} * (d - 0{,}4\ x) = \underline{16.478\ kNm}$

$12.594\ kNm < 16.478\ kNm$, which means, $M_{Rd} < M_{ed,}$

The **reinforcement degree**, ω, is found, and compared with the minimal and the balanced reinforcement degree. To avoid unexpected construction failures, the reinforcement must reach yield strain, ε_{yd} before the concrete reaches its ultimate strain, ε_{cu3} and fails. (Jensen, 2002, p.108). In the balanced cross section the steel will yield and concrete failure will occur at the same moment. In the under reinforced beam the reinforcement will reach ultimate strain ε_{uk} before the concrete reaches ultimate strain.

The condition $\boldsymbol{\omega_u < \omega < \omega_{bal}}$, must be fulfilled to ensure a proper reinforcement degree.

$\omega = \frac{A_{s} * f_{yd}}{b * d * \eta * f_{cd}} = \underline{0{,}55}$

$\omega_{bal} = \lambda * \frac{\varepsilon_{cu3}}{\varepsilon_{cu3} + \varepsilon_{yd}} = 0{,}48$

$\omega_{u} = \lambda * \frac{\varepsilon_{cu3}}{\varepsilon_{cu3} + \varepsilon_{uk}} = 0{,}05$

$0{,}05 < 0{,}45 < 0{,}48$ which means, $\omega_u < \omega < \omega_{bal.}$

The beam is thus not over-reinforced.

The cross section is verified by the same method for **the positive moment reinforcement**:

$b = 1300\ mm,\ h = 1300\ mm,$

$d = 1208\ mm$

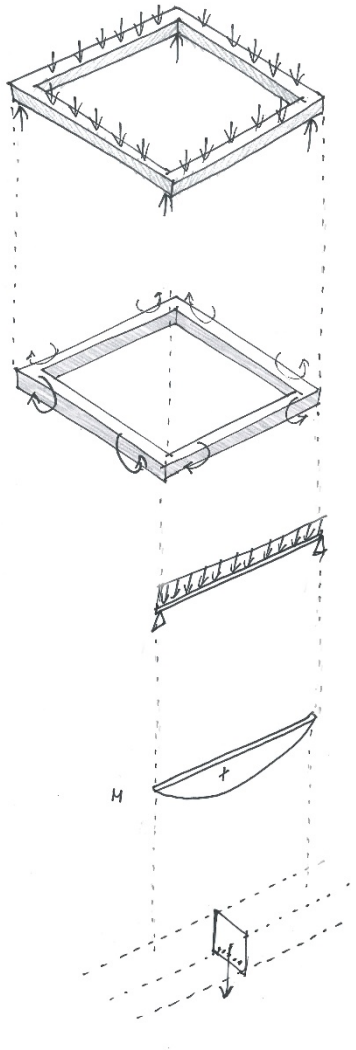
Reinforcement of $26\ bars\ of\ r = 16\ mm$

$x = 297{,}6\ mm$

$M_{rd} = 9.629\ kNm > M_{ed} = 7.542\ kNm$

$\omega_u = 0{,}05 < \omega = 0{,}20 < \omega_{bal} = 0{,}48$

2.3.2 Vertical loading



In the case of the vertical loading of the beam, the supports cannot be considered as fixed beam, as the bending moments are not transfrerred between frame and columns. The beam is now considered as **simply supported**.

Hence, the **bending moment** is:

$$M_{Ed} = \frac{1}{8} * q * L^2 = \frac{1}{8} * 52{,}0\ \frac{kN}{m} * (30{,}6\ m)^2 = 6.413 kNm$$

Reinforcement:

17 pieces of r = 16 mm, in 1 layer

$A_s = 13665{,}28\ mm^2$

The height of the **neutral line, x,** is found:

$x = 1{,}25 * (A_s * f_{yd}) / (b * f_{cd}) = 210{,}8\ mm$

The **breaking moment** is found:

$M_{Rd} = A_s * f_{yd} * (d - 0{,}4\ x) =$ <u>7.263,41 kNm</u>

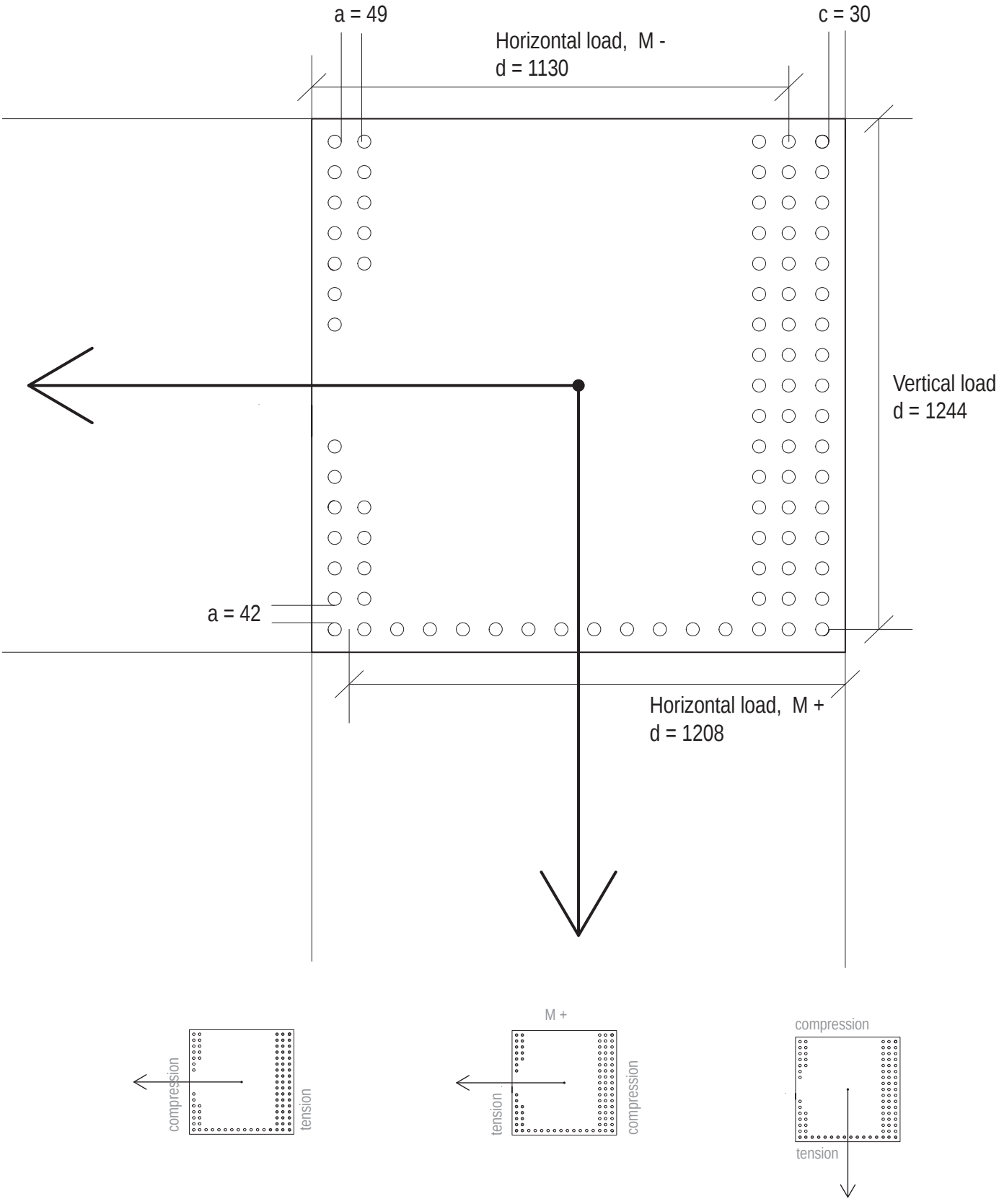
$6.413\ kNm < 7.263{,}41\ kNm$, which means, $M_{Rd} < M_{ed,}$

Reinforcement degree:

$$\omega = \frac{A_s * f_{yd}}{b * d * \eta * f_{cd}} = 0{,}14$$

$0{,}05 < 0{,}14 < 0{,}48$ which means, $\omega_u < \omega < \omega_{bal}$

2.3.2 Cross section diagram



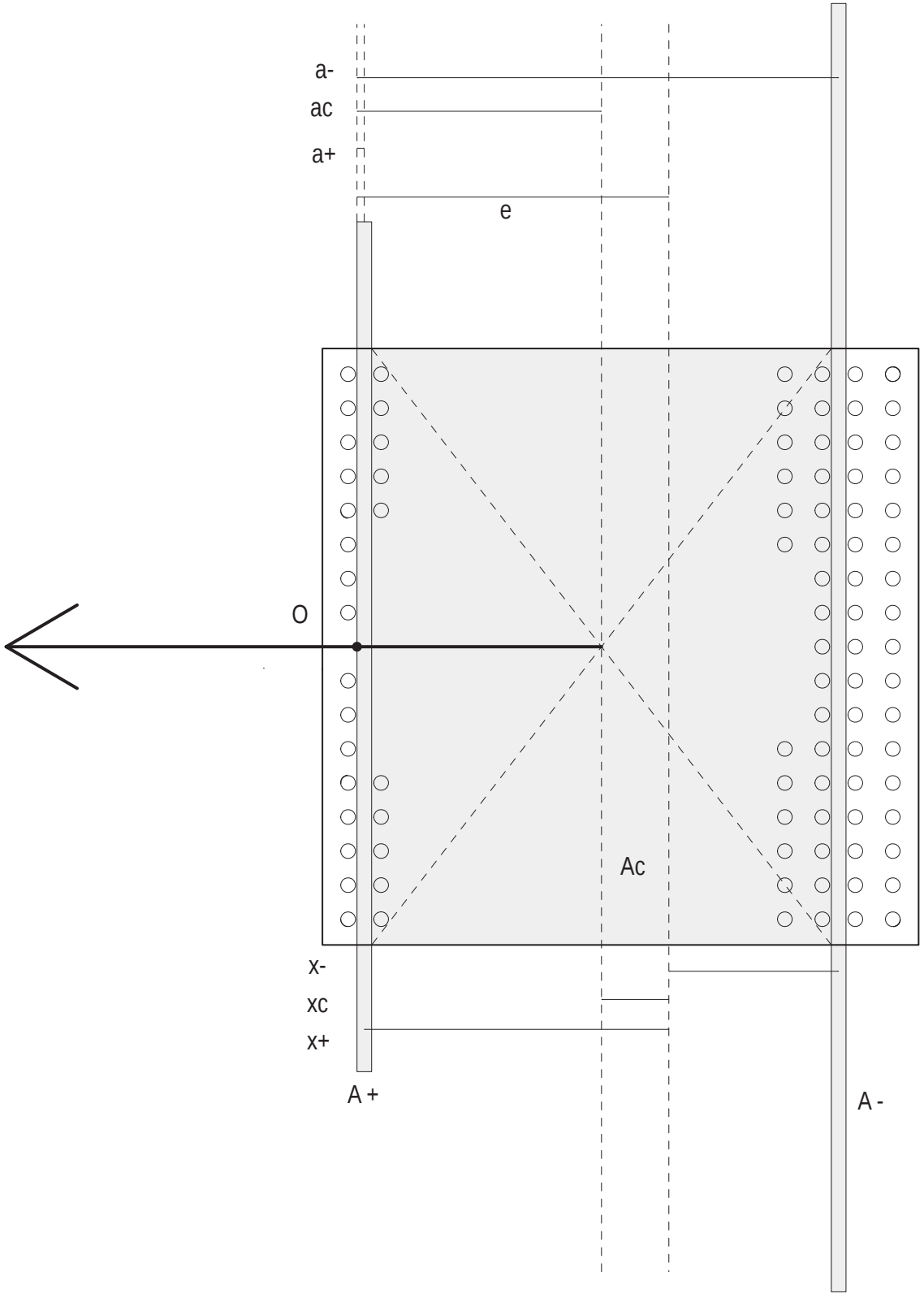
	Horizontal load – Negative M	Horizontal load – Positive M	Vertical load
q	193,3 kN/m	193,3 kN/m	54,8 kN/m
M_{Ed}	15.083 kNm	7.542 kNm	6.413 kNm
M_{Rd}	16.480 kNm	9.629 kNm	7.236 kNm
ω	0,45	0,20	0,14

2.4 Deflection - SLS

To show that the beams are stiff enough the deflection is checked due in to the horizontal loading.

Reinforced concrete is a **composite material** with steel and concrete materials of different elasticity. To calculate the cross section as if it were from a homogeneous material, the geometry of the reinforcement bars is **transformed to an equivalent concrete cross section**, following the method in “Statik og Styrkelære”, p. 195 (Madsen, 2010).

Because of the many rebar layers, some simplifications are made –reinforcement in the bottom is ignored. The transformed area for the M+ and M- rebars are placed in the centerline of the total bar layers in each side.



The area of the transformed cross section is proportional with the relation of concrete and steel Young modulus.

$\alpha = \frac{E_s}{E_c}, A_{tr} = A_s * \alpha$

The deflection can be examined as long or short term, as the Young's modulus of concrete changes due to creep over time.

$E_{short} = 25000\ Mpa$, $E_{long} = 6200\ Mpa$

$\alpha_{short} = 8, \quad \alpha_{long} = 32$

The position of the **neutral line, e**, corresponds to the **center of gravity** of the whole transformed cross section shape. It is found by considering the contribution of a part rectangles to the moment around point 0.

$(A_s + A_{top} + A_{bottom}) * e = A_s * a_s + A_{top} * a_t + A_{bottom} * a_b$

$e = 680{,}25\ mm$

The **area moment on inertia, I_0,** of the whole transformed cross section is a sum of the parts, I_t, weighted according to their distance from the neutral line:

$I_0 = (I_{Ac} + {a_c}^2 * A_c) + \left(I_{Atop} + {a_t}^2 * A_{top}\right) + (I_{Abottom} + {a_b}^2 * A_{bottom})$

$Io = 0{,}67\ m^4$

The **deflection** is found by:

$u_{max} = \frac{1}{384} * \frac{q*l^4}{E*I}$, (Jensen, 2010, p. 109)

$q = 177{,}4\ kN/m$, corresponding to the horizontal comp of cable 1, sag = 0,61 m, m = 225,04 kg/m (Load comb. **SLS**, see 1.2)

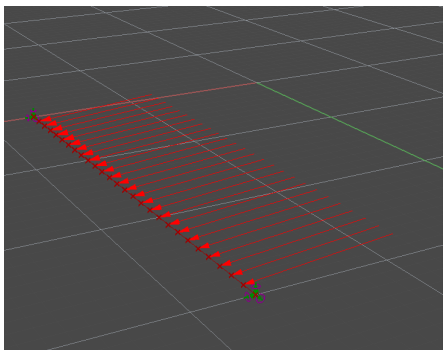
hence,

$u_{short} = 56\ mm$, $ulong = 104\ mm$

If a deflection of $\frac{L}{250} = \frac{30{,}6\ m}{250} = 0{,}122\ m$, is set as acceptable (Jensen, 2008 p.89), then the **deflections cause no problems**.

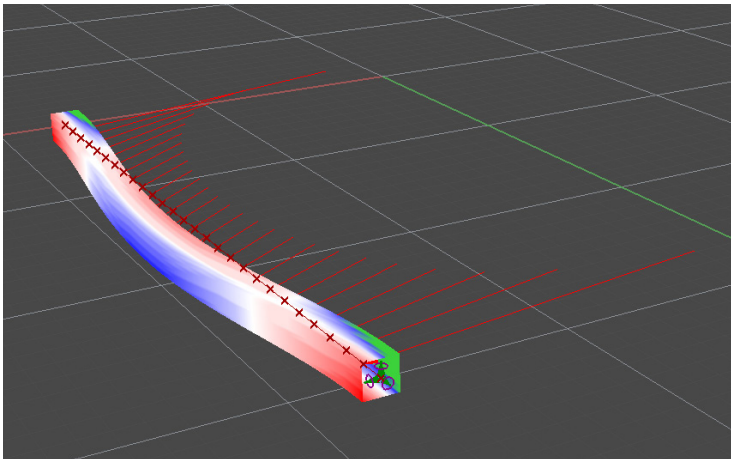
The Karamba parametrical plugin can visualize deflections and stresses in construction members. It is used to compare the deflections when the simplified and the varying load is applied. As seen on the right, the load assumption has great consequence for the deflection result. The assumption means the the beam is overdimentioned and will not fail, but when investigating the deflections the accuracy can be questioned.

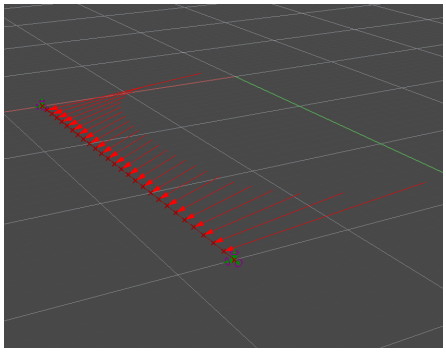
The analysis also allows to vizualize the distribution of tension (blue) and compression (red) along the beam, already described as negative and positive moments earlier. As seen below the maximal stresses occur at the supports. When comparing to the diagrams below, two points of inflection can be identified. They appear as white areas on the beam where the cross section is not subjected to any stresses.



Vectors for the constant load applied in the hand calculation, correspond to cable 1 in Tab 1.

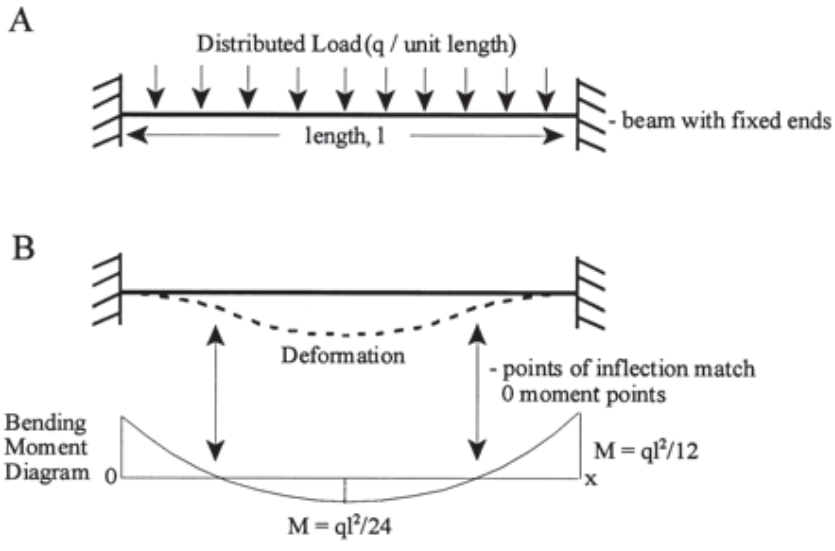
$u_{short} = 43$ mm, $u_{long} = 104$ mm





Vectors for the varying load applied in the Karamba vizualization, correspond to values in Tab 1.

$u_{short} = 27$ mm, $u_{long} = 12$ mm



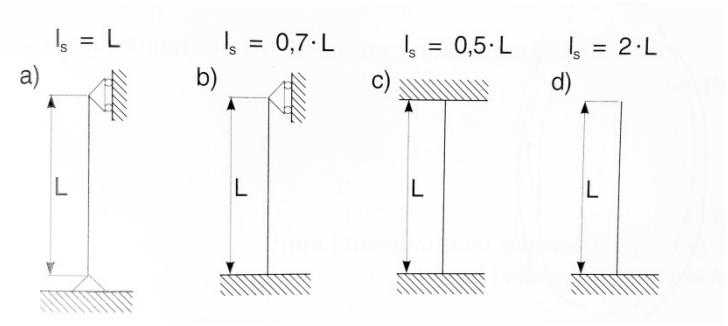
(thestructuralmadness.com)

2.5 Column - ULS

The columns are oversized to fit the dimensions of the beams and appear as a special frame. In the following, the bearing capacity is proven.

The column is **fixed in one end** and free in the other, as the connections between the beams and the top of the column are pinned.

$L_{eff} = 2*L$



(Madsen, 2010, p. 241)

Geometry:

b = 1300 mm, L = 5200 mm, C30

Reinforcement:

4 bars, r = 16 mm, A_s = 3215,36 mm²

Mat data		
f_{cd}	21,4	MPa
f_{yd}	458,3	MPa
E_c	6200	MPa
E_s	200000	MPa
E_0	21428,5	MPa
α	32	

Loads:

Roof weight, including snow weight (as in ULS load combination 1.2):

g_{roof} = *490,46 kg/m²* 0,0098 = 4,0 kN/m²*

Load area pr column:

A_{roof} = *25,60 m * 25,60 m * $\frac{1}{4}$ = 163,84 m²*

Beams:
g_{beams} = *1,3 m* 1,3 m * 30,6 m * 2300 kg/m³ * 0,0098 = 1165,63 kN*

Total load pr column:

P_d = *1165,63 kN + (4,0 kN/m² * 163,84 m²) = 1821,01 kN*

Slenderness:

$\lambda = \sqrt{12} * \frac{l}{h} = 27{,}7$

Critical stress:

$$\sigma_c = \frac{f_{cd}}{1 + \frac{f_{cd}}{\pi^2 * E_0} * \lambda^2} = 19{,}88\ MPa$$

$\sigma_s = \alpha * \sigma_c = 616{,}24\ MPa$

Bearing capacity:

$N_{cr} = N_c + N_s = A_c * \sigma_c + A_s * \sigma_s = 35.659\ kN > 1821{,}01\ kN$

$N_{cr} > P_{total}$

2.6 Conclusion

The roof construction of the museum is not a standard structure and would require a more detailed analysis than this one to fully prove its' constructional durability. The most challenged member of the roof construction is the edge beam. The simple calculations show, that the chosen cross sections are sufficient to withstand the applied bending moments from self-weight and the cable drag. Many simplifications are applied in the calculations, but measures are taken to count in the worst cases.
The frame construction ensures, that the bending moments from the horizontal cable forces are not transferred to the columns. This condition means high requirements for the corner connections between the beams. They will have to withstand the maximal bending moments that appear along the beam, working in opposite directions.
The columns are much bigger than they need to be to carry the vertical forces. They have to withstand horizontal loads though, as the frame construction has no other stiffening elements.

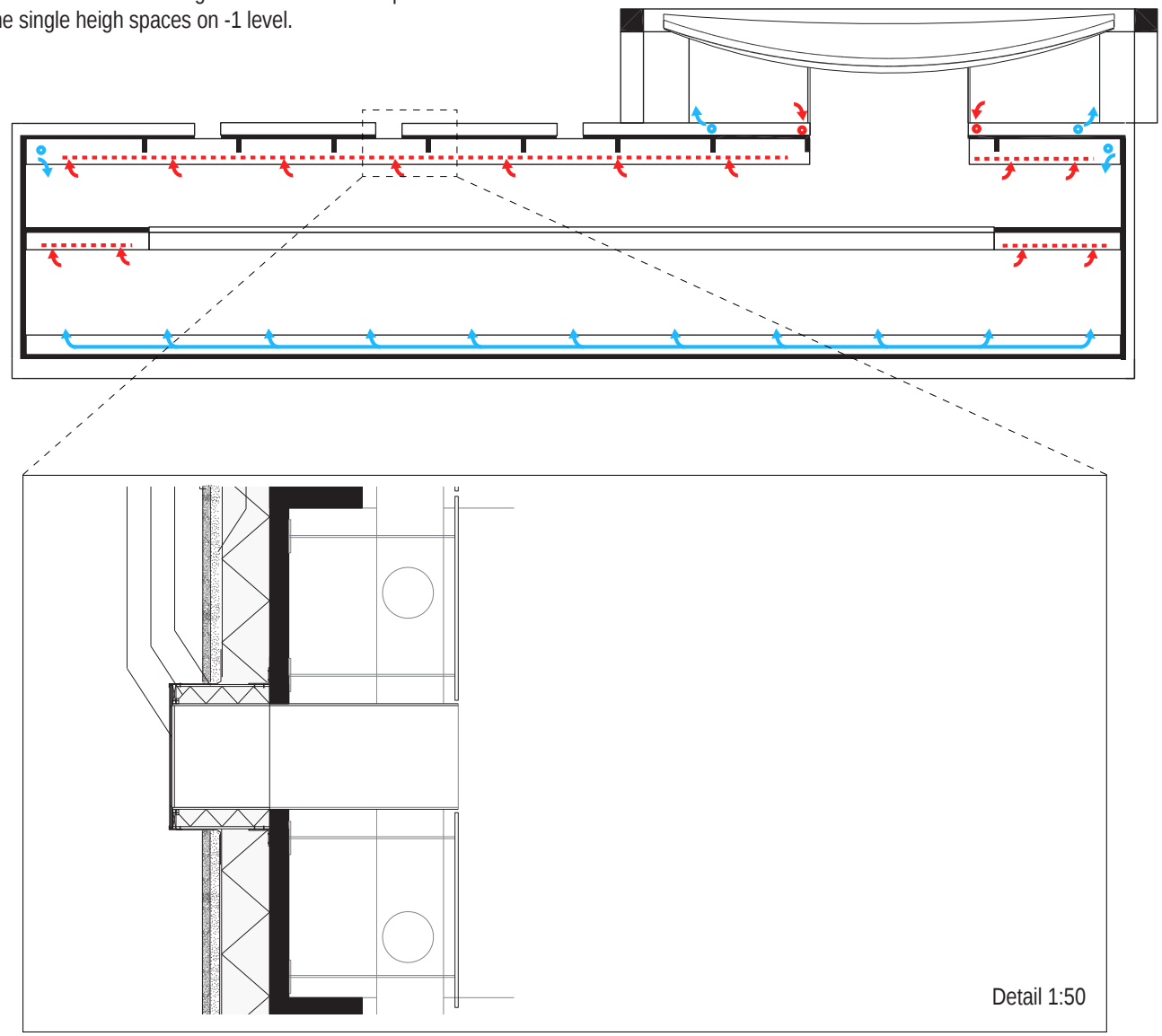
3 Installations

3.1 Mechnical ventilation

The following diagram shows the principles of the ventilation ducts in the museum, to show how the installations influence the deck thickness.

The hanging roof implies, that on the ground floor level all pipes must be led in the floor. The inlets can be coupled with convectors in the floor. The air will then be blown in near the glass facades to prevent cold drafts. The outlets are placed in the opposite side of the room, to allow an even distribution of fresh air.

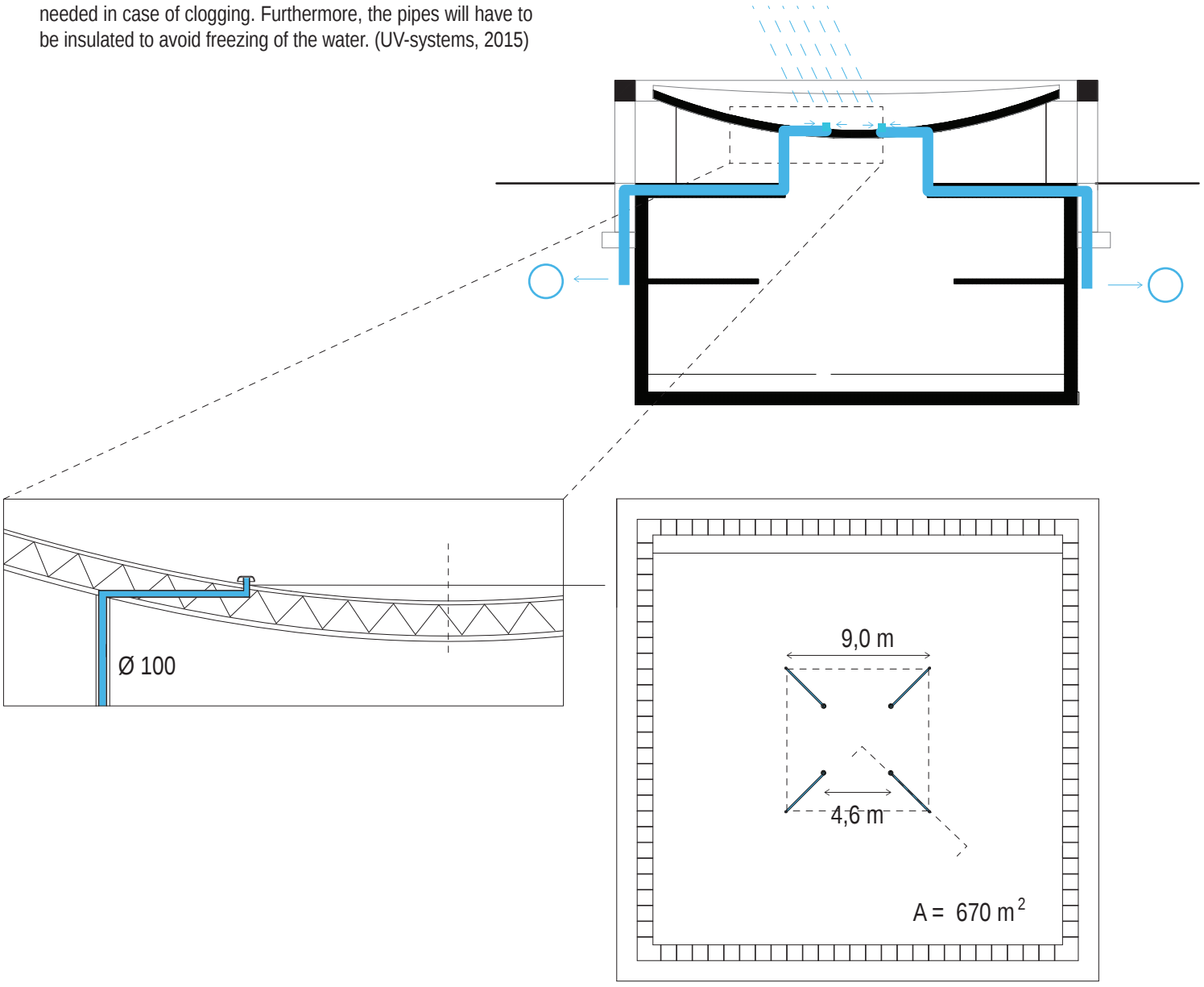
The museum spaces will be ventilated with a separate system. In the double heigh space air is blown in at floor level, and sucked out in the ceiling. Additional inlets are provided for the single heigh spaces on -1 level.



3.2 Rainwater drainage

The convex roof shape requires a custom water draining system. The pipes are led in the roof construction, and down in the corners of the internal glass partition. The middle of the roof needs to be shaped with a fall towards the pipe inlets.

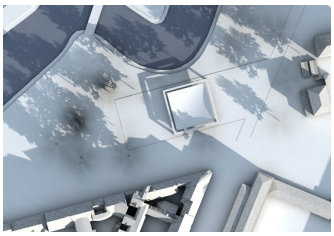
A UV-system is employed where waterfilled pipes allow a so-called full-bore flow. The principle of connected vessels allows the water to flow in pipes with no inclination, when the valve is filled with water. A UV-system allows minimizing the dimentions of the water pipes, as their fill
factor is close to 1. For safety reasons multiple drains are needed in case of clogging. Furthermore, the pipes will have to be insulated to avoid freezing of the water. (UV-systems, 2015)



4 Shadow study

The snapshots from different times of the year show at what times the museum pavilion will receive direct sunlight. The buildings to the south cast shadow on the museum in the winter months, but around the equinow in march the shadow become short enough to expose the pavilion to sun at all times of the day.
In general the building site recieves mostly shadows from the trees. It is beneficial as the foliage provides shading in summer, but not in winte when light is needed.

20th March/Nov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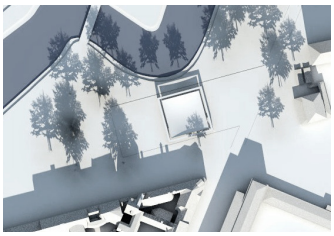
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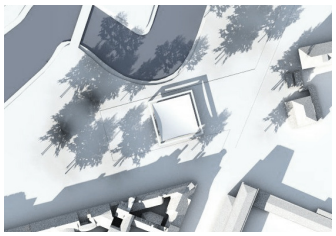
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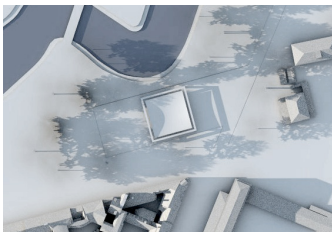
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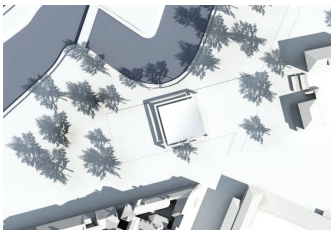
20th of June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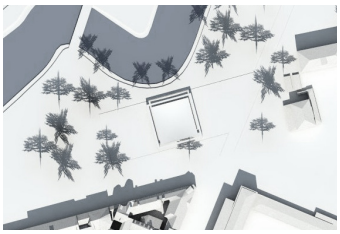
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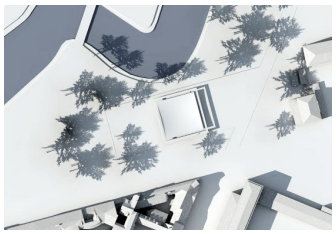
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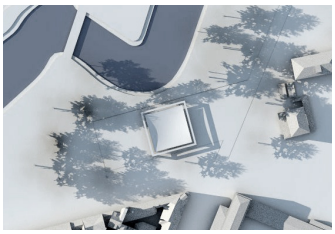
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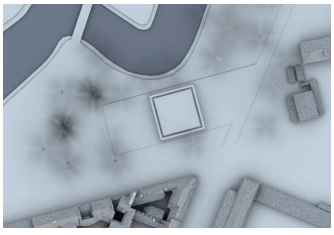
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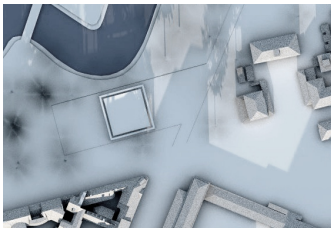
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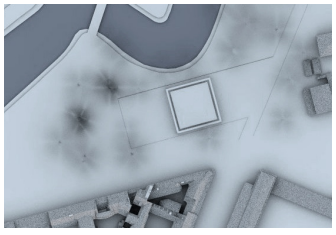
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