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Movable Footbridge in Copenhagen

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Institute of Structural Design

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AFFIDAVIT

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PREFACE

One of my earliest encounters with the significance of bridges dates back to my early childhood when I was about 6 years old. Our family was driving to the south of Croatia for a holiday and I remember being stuck in congestion for hours. This was before navigation systems were available and so my dad was looking at an old map, trying to find an alternative route. I remember him saying that there was a longer but less known route through Bosnia and Herzegovina that could save us some time. After driving a couple of hours and crossing the border, we followed the road along a river to a small town. The map we used showed a bridge crossing the river somewhere in the city and we were desperately searching for it. After enquiring with the locals about the bridge, they informed us that it was destroyed during the war a few years previously and there was no other option but to drive back the same way we came, which was more than 100 kilometres on badly maintained roads.

My enthusiasm for bridge design began in the 1st semester of my master's programme when I attended a lecture by the British architect Martin Knight, who presented his Lower Hatea River Crossing project from New Zealand. The concept for this movable highway bridge was based on the shape of Māori ceremonial fishing hooks and the bridge was named Te Matau a Pohe (The Fish Hook of Pohe, after a famous tribal chief) by the elders of the local Maori tribes. The most inspiring aspect of the project was not the simplistic beauty of the bridge itself but the successful synthesis of architecture, function and native tradition.

In 2018, I worked at Knight Architects as an architectural assistant and had the opportunity to work on various different bridge projects. Among these was the Rotherhithe Crossing in London, UK. If built, the vertical-lift bridge for pedestrians and cyclists between Rotherhithe and Canary Wharf would be the longest of its type in the world.

My goal with this master thesis is to further explore bridge design by learning from the city of Copenhagen. A key reason for its success in becoming one of the most liveable cities has been the promotion of cycling and good infrastructure, in which bridges play a substantial role. The aim is to identify a site and design a new movable bridge that will serve the city's need for better and safer cycling infrastructure.

ABSTRACT

This master thesis focuses on the role of footbridges in Copenhagen, which is one of the most bicycle centric cities in Europe. The first part examines the key factors that make Copenhagen a model city for a well-developed cycling network and how good bridge infrastructure contributes to that end.

As the city continues to expand outward, with residential developments replacing former industrial districts and entire islands being erected from the sea, continuous efforts in the field of bicycle infrastructure are needed to achieve the mobility and climate goals of the city.

The core of the thesis is a proposal for a new movable footbridge over the harbour, linking the newly developed residential district of Teglholmen with the Amager Natural Park. The aim is to provide a comfortable and pleasant crossing experience for commuters and recreational users by taking advantage of the constraints and positively responding to the character of the urban and natural context.

ABSTRAKT (GERMAN)

Diese Masterarbeit befasst sich mit der Rolle von Fußgängerbrücken in Kopenhagen, einer der fahrradfreundlichsten Städte Europas. Der erste Teil befasst sich mit den Schlüsselfaktoren, die für den Erfolg Kopenhagens als Modellstadt für den Radverkehr verantwortlich sind. Insbesondere trägt ein gut ausgebautes Brückennetz zu diesem Erfolg bei.

Die Stadt expandiert. Im Norden wachsen ganze Inseln aus dem Meer und im Süden werden die ehemaligen Industriegebiete durch Wohngebiete ersetzt. Um die Mobilitäts- und Klimaziele der Stadt zu erreichen sind kontinuierliche Anstrengungen auf dem Gebiet der Fahrradinfrastruktur erforderlich.

Der Kern der Arbeit ist ein Vorschlag für eine neue bewegliche Fußgängerbrücke über den Hafen, die das neu entwickelte Wohnviertel Teglholmen mit dem Naturpark Amager verbindet. Ziel ist es den Pendlern und Freizeitnutzern das Erlebnis der Überquerung möglichst angenehm und komfortabel zu gestalten. Hierzu werden die Potenziale der örtlichen Randbedingungen bewusst genutzt um eine angemessene Antwort auf den Charakter des städtischen und natürlichen Kontextes zu formulieren.

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I. BRIDGES AND ARCHITECTURE

Bridges are arguably some of the world's most captivating and inspiring structures. They have been built, admired, fought over, burned, demolished and rebuilt ever since we began conquering the elemental barrier of water and valleys.[1] As objects, they evoke emotions of joy, fear, triumph, a sense of wonder and despair.

Bridges are structures with a service life of 120 years, exceeding that of buildings and other common structures by 70 years.[2] They are seen and utilised by successive generations and often become symbols of the place where they stand. They also present an opportunity to provide social, aesthetic and cultural value. Failure to take these factors into consideration during design while focusing solely on minimising costs risks creating a structure that lacks inspiration and character.

Architecture is playing an increasingly important role in bridge design and interdisciplinary collaboration is becoming common practice, especially in the case of footbridges. Clients are beginning to recognise the added value of a well-designed infrastructure and are turning to architects for their question-based approach to problem solving. Bridge engineers are exceptionally good at finding the most efficient solutions to complex problems, but sometimes this extremely narrow focus neglects the phenomenological aspect. There are, however, several engineering practices that place substantial emphasis on the architecture of a bridge and often employ architects as part of the design team and vice versa.

Although bridges are undoubtedly engineering structures, the wider public does not view bridges and other components of infrastructure as data and stress calculations; they experience the reality in a physical sense.[3] The main questions asked by engineers are what and how, whereas architects are trained to ask why and who. By bridging both skill-sets, there is a much higher potential for creating something powerful. The most outstanding designs are a consequence of successful cooperation between multiple disciplines and an understanding that the true value of a bridge consists of a balance between positive assets and low costs.[4] In a perfect bridge, the aesthetics and engineering are completely interwoven and the design harmonises with its context and setting in a way that makes it looks like it was always there.[5]

1 See Dupre 2017, Foreword.
2 See Calgaro/Tschumi/Gulvanessian 2010, 216.
3 See Martin Knight, BIM and the Art of Motorcycle Maintenance, 8.9.2017, https://structurae.net/en/literature/conference-paper/bim-and-the-art-of-motorcycle-maintenance?downloadFullPdf=1, 2.6.2020
4 See FIB 2005, 5-6.
5 US Modernist Radio: Podcast #146/Bridges as Architecture: Europe's Martin Knight, 2.6.2020.

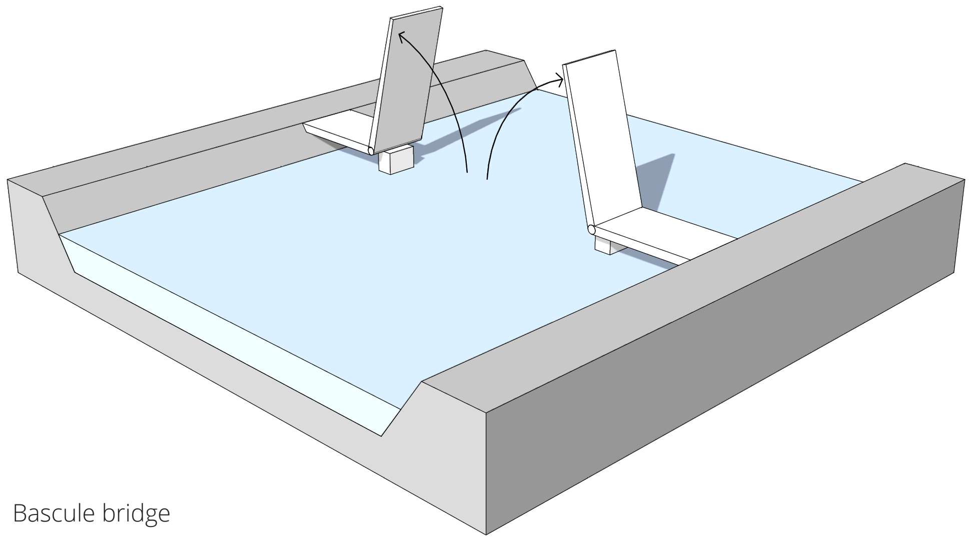
Knostrop Footbridge | Leeds, UK

I.I. FOOTBRIDGES

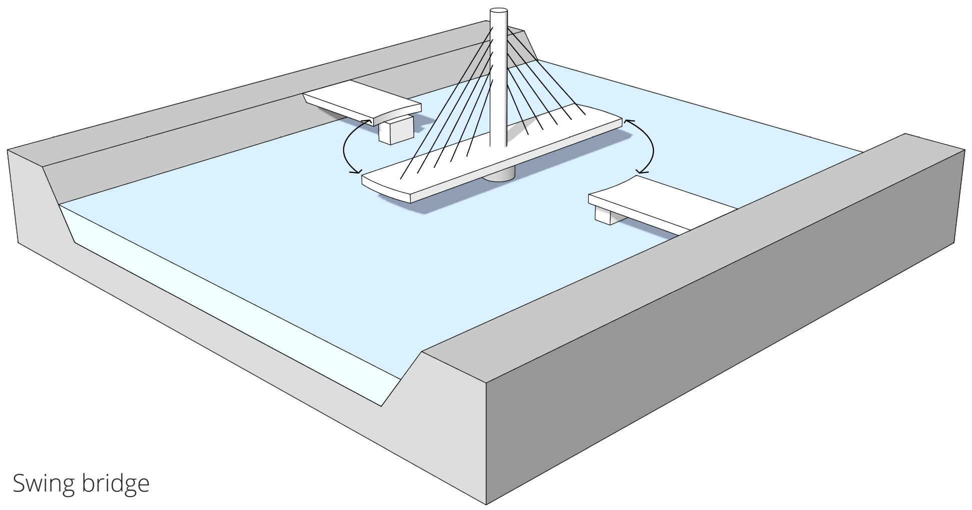
The evolution of bridges since humans first crossed a stream of water on a fallen tree trunk has been substantial. Footbridges have a much longer history than road bridges, which only appeared at the end of the 18th century as a result of industrialisation and the increasing importance of mobility and traffic.[6] Since the beginning of the industrial revolution, bridges began to demand ever higher standards to meet the safety provisions needed for higher traffic loads, which required qualified experts in structural engineering. Bridges of ever longer spans were being built across the industrialised world at a much faster rate than before and their contribution to economic growth was immense. Design was beginning to be pervaded by the principles of economy. However, something was slowly being lost in the process. With fewer structural constraints and economics being the major driving force, less consideration was given to the site and aesthetics of bridges. The clearest example of this today is that of highway overpasses where standardised solutions are being repeatedly applied to reduce costs. Consequently, most regular people began to see bridges purely as utilitarian structures and their storytelling aspect slowly diminished.

Footbridges have always constituted a genre of their own in the broader field of bridge construction. Due to their human scale, we have a more personal relationship with them, compared to road bridges where we do not get to experience finer details and materials. The experience of crossing, tactile interaction, the views, the setting and so on are extremely important aspects to consider in the design of a footbridge. While structural demands on footbridges are much lower than on road and railway bridges, more emphasis is laid on the finer detailing such as handrails, surfacing and lighting. Functional requirements also vary substantially and are based on a wide range of factors. While the function of enabling users to cross a barrier is usually of primary importance, footbridges can also serve other functions. In addition to providing a path connecting two points, footbridges may also contribute to the social, aesthetic and cultural value.

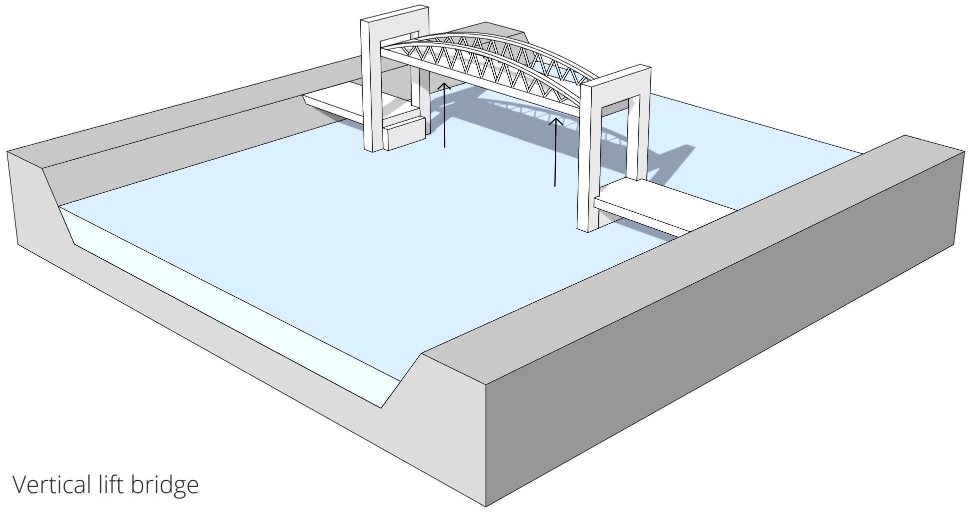
6 See Baus/Schlaich 2007, 11.



Bascule bridge



Swing bridge



Vertical lift bridge

I.II. MOVABLE BRIDGES

There have been numerous schemes developed over the centuries to move bridges. Most can be grouped into a few categories and some have passed into history with only a single example. The three categories of movable bridges in common use today are: bascule bridges, swing bridges and vertical lift bridges. Other types of movable bridges that are less common include retractile, pontoon, folding and a small number of unusual bridge types.[7]

The choice for a particular type depends on functional factors such as opening width, required vertical clearance, opening span length and aesthetic site-specific factors. A vertical lift bridge with large towers may be undesirable in a natural setting while the opening curve of a swing bridge may interfere with existing structures. Ideally, the opening mechanism should not dictate the design but rather complement it.

BASCULE BRIDGES

The word bascule is French for seesaw. It is more commonly applied to balanced bridges that pivot around a horizontal axis which lies near the centre of gravity at a right angle to its longitudinal centreline. The balance is usually uneven and the weight distribution depends on the open or closed state of the main bridge. A large number of bridges pivot around a horizontal axis but are either not balanced or do not take the configuration of a seesaw (e.g., rolling bascule). Such bridges may also be called bascule bridges as the accepted usage of the word encompasses all bridges that pivot in the same manner.[8] Bascule bridges without a counterweight may be considered where space is limited and an over deck solution, such as a rolling bascule or vertical lift, is undesirable.

The fundamental difficulty with real bascule bridges is that the back end must inevitably go down when the bridge is being opened. If the deck is close to the water surface there is not much space for the counterweight before it dips into the water. Most variations tackle this problem in numerous innovative ways, which range from widely adopted standardised solutions to entirely unique approaches.

Bascule bridges can be single leaf or double leaf types. Double leaf bascules are usually preferable as they offer numerous advantages over single leaf bascules, such as quicker opening time, lower wind resistance, simpler machinery, smaller counterweights and in some cases greater navigation clearance in the closed position due to the tapering of the girder towards the middle. The biggest disadvantage of double leaf bascules over single leaf bascules is the doubling of most of the components as this creates a higher risk of part failure.

7 See Koglin 2003, 20.
8 Ibid., 33-35.

SWING BRIDGES

Swing bridges rotate on a horizontal plane and, in most cases, consist of a central pier housing the rotating bearing and two cantilevers of equal length. In some variations, the cantilevers can also have variable lengths and may therefore require an additional counterweight. There are rare instances where a swing bridge would be preferable to other types. Their main advantages are that they do not project into the air when opened and may be preferred in locations where high wind loads can be an issue. The biggest concern with swing bridges is that they rely on the mechanism to a much greater extent, require more maintenance and are usually slower to operate than other bridge types.[9] They also need relatively large supporting piers to accommodate the mechanism and occupy more space as they require a lateral clearance equal to the length of the cantilevered parts.

VERTICAL LIFT BRIDGES

A bridge of this type consists of a movable span, most commonly a truss, that is lifted vertically using fixed levitation towers. These towers are mostly free standing, but in special cases can also sink into the foundations. The towers are generally equipped with a counterweight that is attached to the lifting span using a steel cable which passes over rotating sheaves on the top of the tower.[10] Vertical lift bridges are most commonly used for longer spans, as the movable section is supported on both ends at all times, in contrast to a cantilevered system of bascule and swing bridges. They can be a more economical alternative to other types of movable bridge when unlimited height clearance is not required and the tall towers do not interfere with the wider context.

9 See Koglin 2003, 96-97.
10 Ibid., 55.

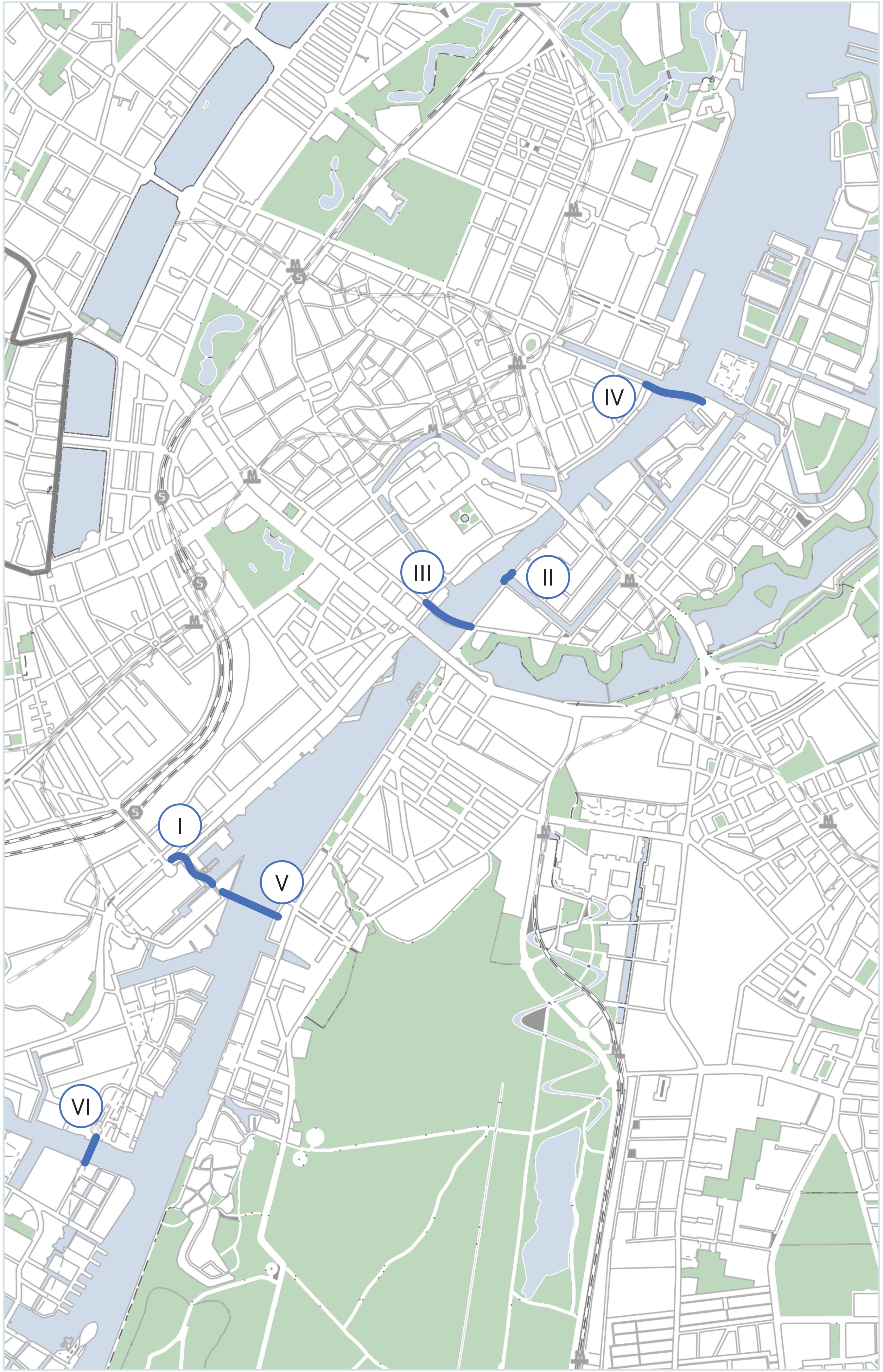
Cyclists at Nørrebrogade in Copenhagen (1940-45)

II. **BRIEF**

Copenhagen is globally perceived as a model city due to its well-developed cycling infrastructure. Hundreds of city officials from all around the world come to Copenhagen every year to study and learn from the city's successful efforts in making the bicycle the most efficient transportation method. Although the bicycle has been a staple of Copenhagen since the beginning of the last century, it has experienced fluctuations in popularity. After a peak in cycling in 1949, the city saw a rapid rise in the number of cars which required a reconfiguration of public spaces to accommodate them. The lack of cycling infrastructure caused a drop in the modal share of bicycles to 20% and the rate of cycling fatalities to spike at an all-time high. This triggered massive demonstrations where people demanded safer conditions for cyclists. The re-prioritising of the bicycle began in the early 1980s when the improvement of infrastructure began to accelerate.[11]

Over the past decade, Copenhagen has witnessed profound changes in its connectivity. The city has excelled in promoting cycling over the decades and the bicycle has now become the Copenhagener's preferred method of transportation. In 2018, 49% of all trips to work and education were made by bicycle and this percentage is expected to increase. In turn, this has created pressure on the infrastructure. To maintain cycling as the most efficient way to get around, investing in a bicycle-friendly infrastructure must be a priority.[12] The Technical and Environmental Administration released its 2011-2025 Bicycle Strategy, where it identified necessary improvements to existing stretches as well as the need for new infrastructure projects, including several bridges. The port of Copenhagen and the canals pose a considerable obstacle to residents and visitors. To overcome this, 12 new bridges have been built between 2012 and 2020 and more are proposed for the near future. One of the latest additions to the city's series of bridges is the Inderhavnsbroen, which was built in 2016. This retractable free cantilever girder bridge has attracted a considerable amount of criticism, about which more will be said later. Prior to its opening, the city estimated that daily cyclist usership would be between 3,000 to 7,000.[13] The latest numbers from September 2018 show that an average of 15,800 cyclists use the bridge every day.[14] Another example is the Bryggebroen footbridge, built in 2006. This has given the people of Copenhagen a faster, safer and more pleasant commute which is evident from the number of daily users. In the first year of operation it saw an average of 3,500 daily users[15] sky-rocketing to 20,500[16] in September 2018. Together with the 2014 built Cycle Snake, it offers one of the most scenic and enjoyable bicycle routes in Copenhagen. With new residential developments being planned in the north (Lynetteholmen) and south (Sydhavnen) as well as the increasing share of bicycles on the streets, considerable potential remains for new bridges. The data trends clearly indicate that if people are provided with good infrastructure, they will use it.

11 See Coliville-Andersen 2018, Chapter 2. Bicycle Urbanism by Design.
12 See The Bicycle Account 2018, https://kk.sites.itera.dk/apps/kk_pub2/pdf/1962_fe6a68275526.pdf, 2.1.2021.
13 See Coliville-Andersen 2018, Chapter 6. Copenhagen's Journey.
14 See Interactive map of Copenhagen, http://kbhkort.kk.dk/, 21.4.2020.
15 See Bicycle Strategy 2011-2025, https://civitas.eu/sites/default/files/documents/bicycle_strategy_2011-2025_copenhagen_0.pdf, 29.12.2020.
16 See Interactive map of Copenhagen, http://kbhkort.kk.dk/, 21.4.2020.



II.I. PRECEDENT

A good starting point in determining the local design principles is to analyse the successes and failures of similar projects and the cycling infrastructure. There has been a wide range of unique footbridges built in Copenhagen over the last 20 years and these have generally been successful.

Part of the current research included a survey of Copenhagen's residents and commuters that elicited their experiences with the existing bridge infrastructure, as well their desires and comments on footbridges in general (see Appendix). One of the conclusions of the survey was that cyclists place a great deal of value on the experience of crossing the bridge. Two thirds of the respondents considered it one of the most important aspects of a footbridge. This broad concept encompasses the smoothness of the riding surface, scenery, clear separation of pedestrian and cyclist traffic, and integration with the broader cycling network. The most common complaint was the crossing of pedestrian and cycle traffic and unclear separation between the lanes. Cyclists also prefer a curved entry and exit path rather than sudden sharp turns.

The following pages identify the positive and negative design factors of 6 popular footbridges in Copenhagen, based on survey responses, critiques and personal observations.

I The Cycling Snake
II The Circle Bridge
III Lille Langebro
IV Inner Harbour Bridge
V The Quarry Bridge
VI Alfred Nobel Bridge

CYKELSLANGEN - *THE BICYCLE SNAKE*

Designer
Dissing + Weitling, 2014

Length
230m

Structure
Steel girder

Segregation +
Riding experience +
Elegance +
Cohesion +

Control -

Designed by the local bridge design specialist Dissing+Weitling, the bicycle snake is an elevated ramp reserved exclusively for cyclists. Since its opening in 2014, it has become an icon for Copenhagen's cycling infrastructure and attracted a large amount of international attention. It is also the bridge described as most enjoyable by the survey participants.

It serves as an extension of the Bryggebroen, connecting the waterfront with the Fisketorvet shopping centre and the highway. Cyclists can enjoy scenic views when riding over the gently curving bridge and do not have to worry about crossing paths with pedestrians. Underneath, the slow-moving pedestrians also have a more pleasant experience of the harbour. Although the bridge has greatly improved the riding experience, several minor issues need to be addressed. For instance, the popularity of the Bicycle Snake means it attracts a large number of tourists. Although the bridge is bicycle only, some tourists as well as locals are ignoring the signs and entering the bridge on foot. This creates confusion and irritation and can lead to accidents. Another minor issue is the transition between the Bryggebroen and the Bicycle Snake, where the only separation is the painted lines on the paving. Ideally, there should be a material change or height difference to make pedestrians more aware and cautious when crossing a bicycle path.

CIRKELBROEN - *CIRCLE BRIDGE*

Designer
Ólafur Elíasson, 2015

Length
40m

Type
Swing bridge

Innovative +
Spatial integration +
Lighting +
Social value +

Approach ramps -

Cirkelbroen is a bridge unlike any other. It is composed of five thin intersecting circular platforms, each with a central pylon and cables attached to the edge of each platform. The circle intersections form a zig-zag route which reduces the speed of those passing and encourages them to take a break and enjoy the city from a different perspective. The areas on the bridge that are not directly on the main crossing path also function as social spaces for people to meet, relax and chat. The zig-zag pattern is repeated in the parapets which are illuminated by night. The pylons imitate the shape of a sailboat, which is a common sight in Copenhagen. The design successfully reflects the daily life and intimacy that can be found on the canal and around the neighbourhood. As well as its unique overall shape, the opening sequence is just as extraordinary. Three of the five circles function as a swing bridge which rotates to the inside to allow larger boats to pass. To achieve the necessary vertical clearance envelope for smaller boats, the bridge deck is slightly above ground level which means approach ramps had to be built. These straight parallel ramps with glass parapets are out of character and sufficient thought was not given as to whether they fit the overall design.

LILLE LANGEBRO - *LITTLE LANGEBRO*

Designer
Wilkinson Eyre, 2019

Length
160m

Type
Swing bridge

Spatial integration +
Riding experience +
Elegance +
Cohesion +

Segregation -

Lille Langebro is the latest addition to Copenhagen's series of bridges. With over 10,000 daily users, it serves as a relief for the often congested and less bicycle friendly Langebro, which was used by more than 40,000 cyclists daily.[17]

In terms of material, colour and uniformity the design of the bridge is simple yet extremely elegant. The minimal clear deck width is 7m comprising 3m for pedestrians and 4m for cyclists. It is paved in smooth asphalt and the riding experience is very pleasant. The segregation between bicycle and pedestrian lanes is achieved by painted lines only which can sometimes lead pedestrians to wander off to the bicycle lane. With its curved shape, both in plan and section, it merges seamlessly with the banks at the end of Vester Voldgade and Langebrogade. The variable cross section of the triangular beams gives the bridge the appearance of a twisted ribbon. Due to this irregular shape, each parapet post is slightly different yet its uniformity is successfully maintained throughout the bridge. The movable superstructure is supported by four slender steel fingers based on a round concrete pier where the rotating mechanism is discretely concealed so that the lines of the structure flow uninterrupted from one side to the other.

17 See Lille Langebro, https://www.visitcopenhagen.com/copenhagen/planning/lille-langebro-gdk1111450, 21.5.2020.

INDERHAVNSBROEN - *INNER HARBOUR BRIDGE*

Designer
Studio Bednarski, 2016

Length
180m

Type
Retractable/sliding bridge

Innovative +

Cohesion -
Safety -
Out of place -
Complexity -

Built in 2016, the Inderhavnsbroen connects the Nyhavn with the islands of Christianshavn. Prior to the bridge, the only way to cross the port between the two busy parts of the city was by boat. It was estimated that 3,000 and 7,000 cyclists would use the bridge; however, in 2018 there were an average of 15,800 cyclists and 7,900 pedestrians using the bridge daily.[18]

The innovative retractable sliding mechanism gave the bridge its nick name of "The Kissing Bridge". The designers of the bridge prioritised innovation over everything else. As a result, the bridge is rather cumbersome, inconvenient and unsafe to cross due to the unavoidable sharp turns dictated by the opening mechanism. Furthermore, safety is further compromised by the extremely slippery blue paving surface. Since its opening in 2016, many warning signs have been erected, which are always an indication of bad design and lack of appropriate consideration. The tapering and irregularity of the shape give it the appearance of a badly stitched panorama photo and it does not fit well within the delicate urban and historical context of its location. The mechanical complexity was also the cause of major delays in construction and parts had to be replaced a number of times.

18 See Coliville-Andersen 2018, Chapter 6. Copenhagen's Journey.

BRYGGEBROEN - *THE QUAY BRIDGE*

Designer
Dissing + Weitling, 2006

Length
190m

Type
Swing bridge

Elegance +
Cohesion +
Segregation +

Integration -
Vandalism -

Built in 2006, this footbridge provided the first link over the harbour in 50 years, With an average of 20,500 cyclists crossing every day, it is the most frequently used footbridge in Copenhagen.[19]

The 5.5 metre wide deck of the bridge is segregated into a pedestrian path and two bicycle lanes which are physically divided by the main steel girder. With the main load bearing system above deck, this clever solution gives the bridge its slenderness while also separating the two traffic groups. The deck is supported by A-shaped pairs of thin round piers. The Bryggebroen has a single asymmetric swing opening segment on the east side. This results in the opening segment being much bulkier than the rest of the bridge which negatively affects its overall slenderness.

A common complaint among the survey participants was the sharp 90 degree turn cyclists have to make on the east side where the bridge connects to the promenade. The large flat white surface of the main girder attracts a large volume of graffiti and the parapets have become an immensely popular place for the love padlocks. Despite being an essential link, the bridge is not enjoyable for most users.

19 See Interactive map of Copenhagen, http://kbhkort.kk.dk/, 21.4.2020.

ALFRED NOBEL BRIDGE

Designer
COBE, 2018

Length
80m

Structure
Pre-stressed concrete

Social value +
Detailing +
Cohesion +
Segregation +

Supporting piers -

Unlike the other bridges discussed, the Alfred Nobel Bridge is not exclusively reserved for cyclists and pedestrians and is also not movable, which means it cannot be opened for sailors who do not stay below the three metre ground clearance. However, there are lessons to be learned from this. The bridge's unique feature is the city's longest lookout bench which separates pedestrians from car traffic and improves the sense of safety. The 70 metre long sculptural mahogany wood benches offer multi-level seating in rounded, undulating shapes. The widening of the bridge towards the middle disrupts the strict linear motion of users and encourages them to take a rest, enjoy the views and socialise. A great deal of care was also given to the detailing of the bridge. The dense vertical parapet poles merge neatly with the underlying curved concrete structure, forming a unified whole. The choice of tropical mahogany hardwood for seating adds quality and ensures long serviceability.

However, the leaning concrete columns supporting the bowing concrete deck do not have the same finishing quality and disturb the overall elegance of the structure.

II.II. SITE

Determining a site for a footbridge is the first and one of the most important factors for successful bridge design. Unlike road or railway bridges, which in most cases have the sites predetermined, footbridges offer more opportunities to create an impression, confer a special identity on a site and improve an urban area. Selection of the optimal place for a footbridge varies according to context. Primarily, it is based on why a bridge is needed and its intended users.[20] Existing traffic patterns, future development strategies and historic urban developments have to be analysed in order to predict how a bridge will fit within a wider context in the long-term.

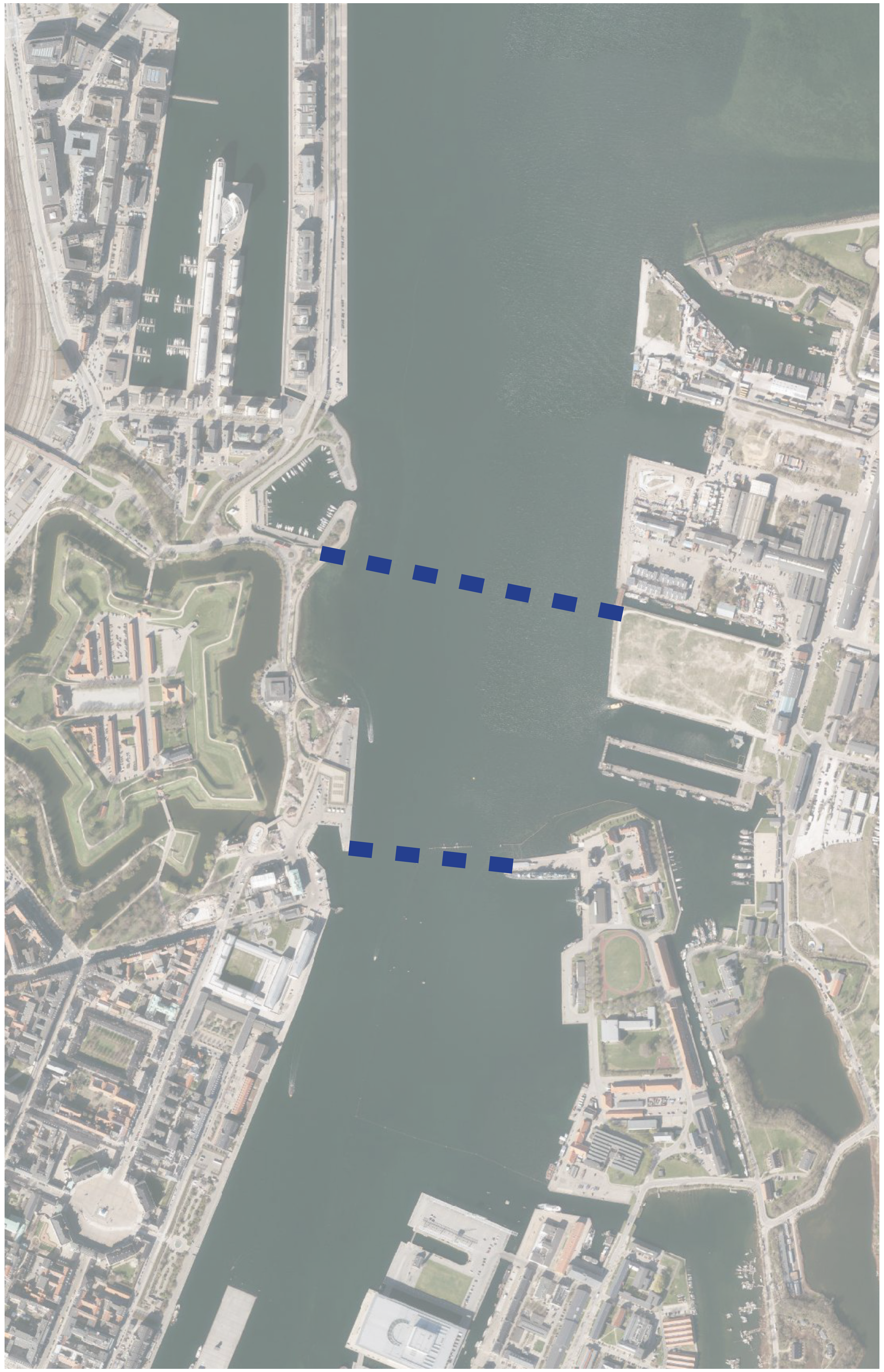
Site topology is another major factor in determining the proper alignment of the crossing. In addition to being a visual fit, a footbridge should also align with the existing routes as seamlessly as possible without sharp or unnecessary turns. The crossing distance should be kept to a minimum unless a longer route would result in a more direct path for the users. A straight line is not necessarily always the most optimal solution and multiple alignment options should be carefully considered before settling on the route most likely to save costs.

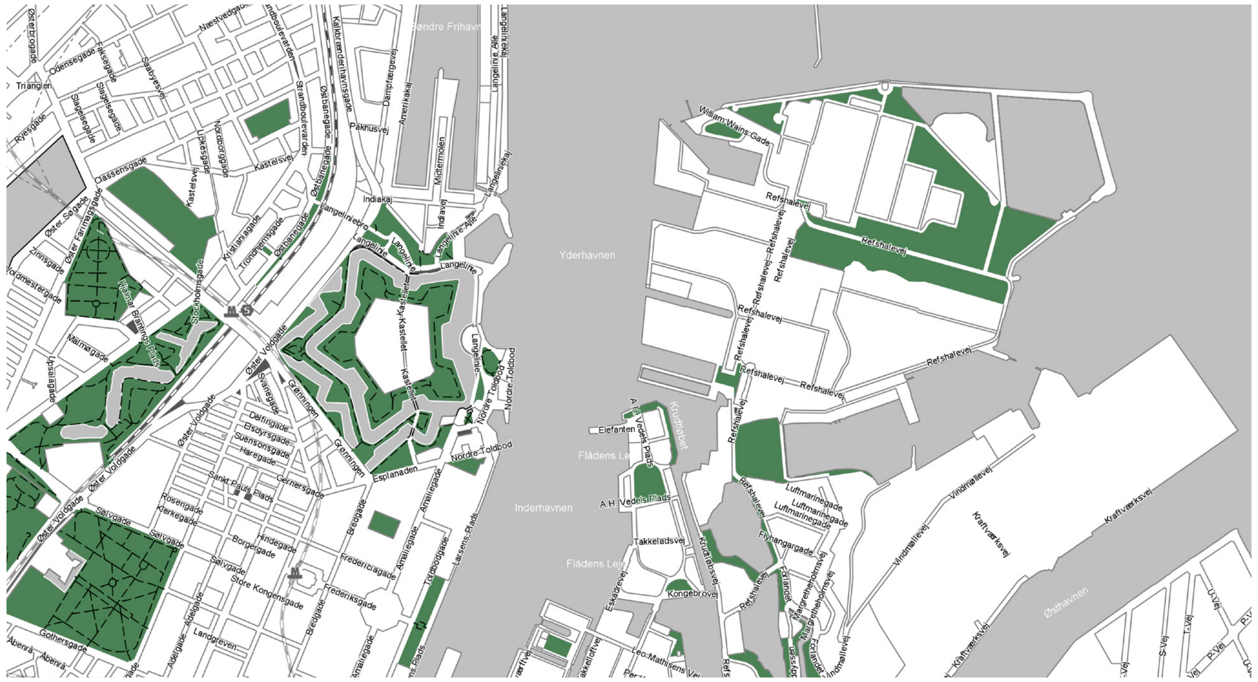
POTENTIAL SITES

Usage of the Port of Copenhagen changed as the city developed south towards the port. Former industrial and port areas have been transformed into sustainable urban neighbourhoods that exploit the great potential for life and activities along the water. After analysing the existing situation, plans for new developments and projections for the future, three potential sites for a new footbridge were identified.

Each bridge site addresses unique problems and poses different design challenges with the common issue for all sites being the rising number of cyclists and potential users. A comprehensive study of each site thus determines the most sensible location for the next footbridge. Once a site is chosen it is then necessary to look deeper into the wider context of the selected area, including its historical development.

20 US Modernist Radio: Podcast #146/Bridges as Architecture: Europe's Martin Knight, 2.6.2020.





SITE A
REFFEN - OSTERBRO

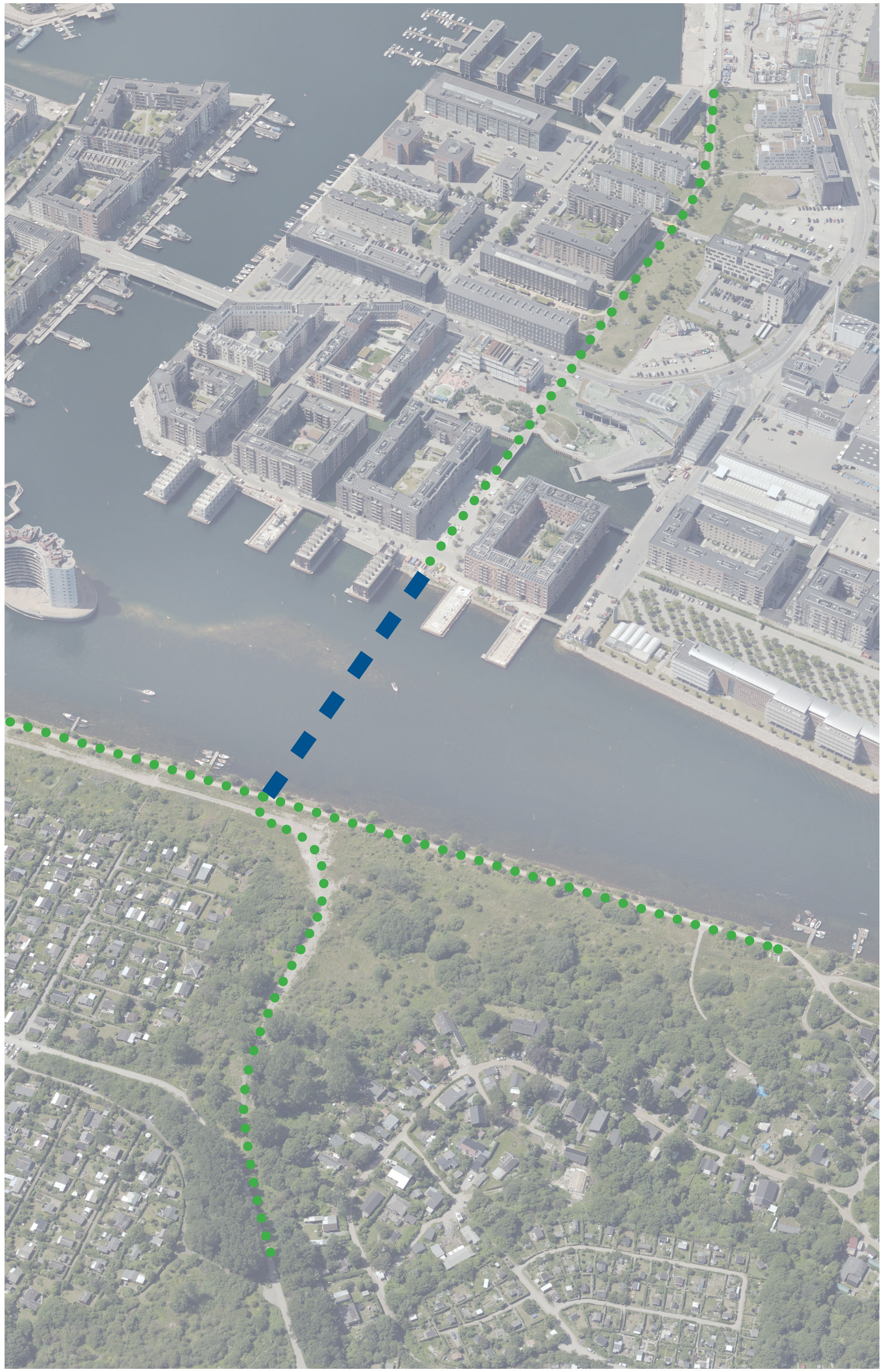
The first and most desirable site according to survey participants lies in the north between Reffen and Osterbro. This mostly industrial area is currently undergoing a transformation with large scale housing developments being planned, including a new island - Lynetteholmen. Currently, the only way to cross the port in the north is by a local ferry. The nearest bridge connecting Reffen to the west side is the Inderhavnsbroen more than 2.5 km to the south. The rising number of residents and daily commuters will require a direct connection between the two sides of the city. Building a bridge in this location will be a substantial engineering challenge, with the total length being approximately three times longer than the inner-city bridges across the main harbour.

A 2008 proposal for a 65-metre-high footbridge by Steven Holl Architects, which would have connected two high-rise towers on each side of the harbour, received substantial criticism and has since been abandoned. While it would certainly have been a landmark and a fun experience to cross, the proposal was highly impractical and would have required users to ascend 30 storeys in order to cross.[21]

Given the uncertain time frame for the construction of the new developments and the urban planning still in progress, determining the most sensible bridge alignment and necessary bridge requirements would be highly speculative. It is also unclear whether a bridge of this scale should be reserved for both cyclists and pedestrians.

A possible future solution includes a mixed-use bridge along with a bypass for car traffic. This would have a positive impact in relieving the city centre of car traffic, giving priority to cyclists and pedestrians.

21 See Peter Walker, 26.11.2015, Copenhagen glass-walled bicycle bridge plans abandoned, https://www.theguardian.com/world/2015/nov/26/copenhagen-gate-glass-bicycle-bridge-abandoned-steven-holl, 2.6.2020.



SITE B

TEGLHOLMEN - AMAGER FÆLLED

The second location, which is also undergoing a considerable amount of urban development, is the Sydhavnen. There have been several new modern apartment complexes built and some are still under construction. In the 2011-2025 Bicycle Strategy, the City of Copenhagen called for large scale bicycle infrastructure improvements in this area, including a number of bridges.[22] Some of them, like the Teglværksbroen and Alfred Nobel Bridge, have already been built but there is still a missing link across the main harbour. Although master plans of the newly developed area show a dotted line over the harbour, no proposal for a bridge has been presented to date.[23]

Sydhavnen is one of the fastest growing districts in Copenhagen. Since 2008 the district's population increased by 44%, compared to 17% for Copenhagen as a whole.[24] It is expected that growth will continue at a similar rate over the next decade with new housing developments like the Enghave Brygge island due to finish in a few years.

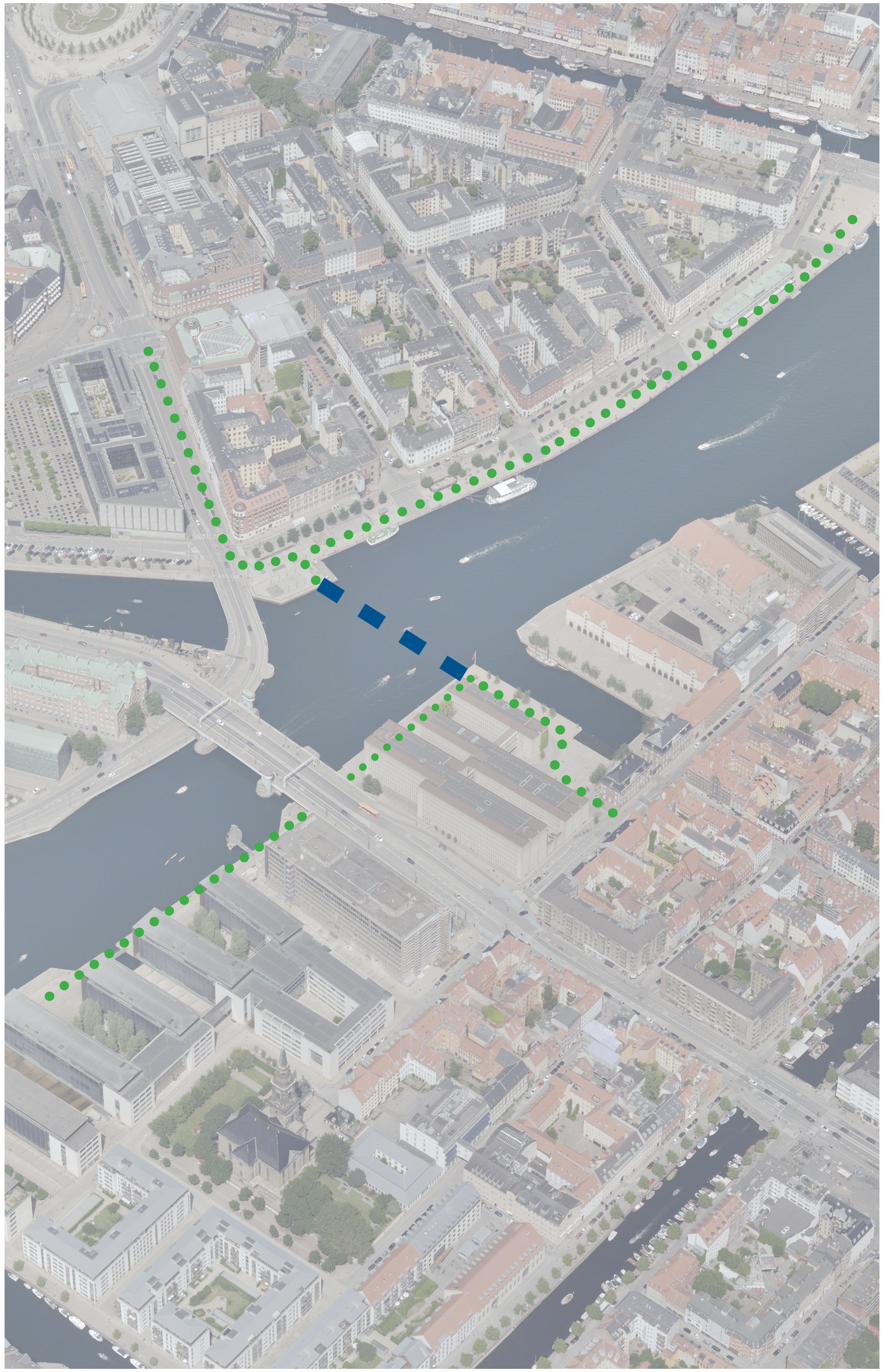
Copenhagen has been actively encouraging urban developers to provide access to green recreational areas for all residents. Studies show that Copenhageners prefer wild nature to artificial parks and would like better access to these.[25] A footbridge in this area would connect the modern urban district with the greener Amager Vest district and provide a shortcut or alternative route for commuters. The residents of the Sydhavnen district would have direct access to the Amager Fælled, which has been labelled the "green lung" of Copenhagen and covers 3,500 hectares offering wide-open landscapes with rich wildlife.

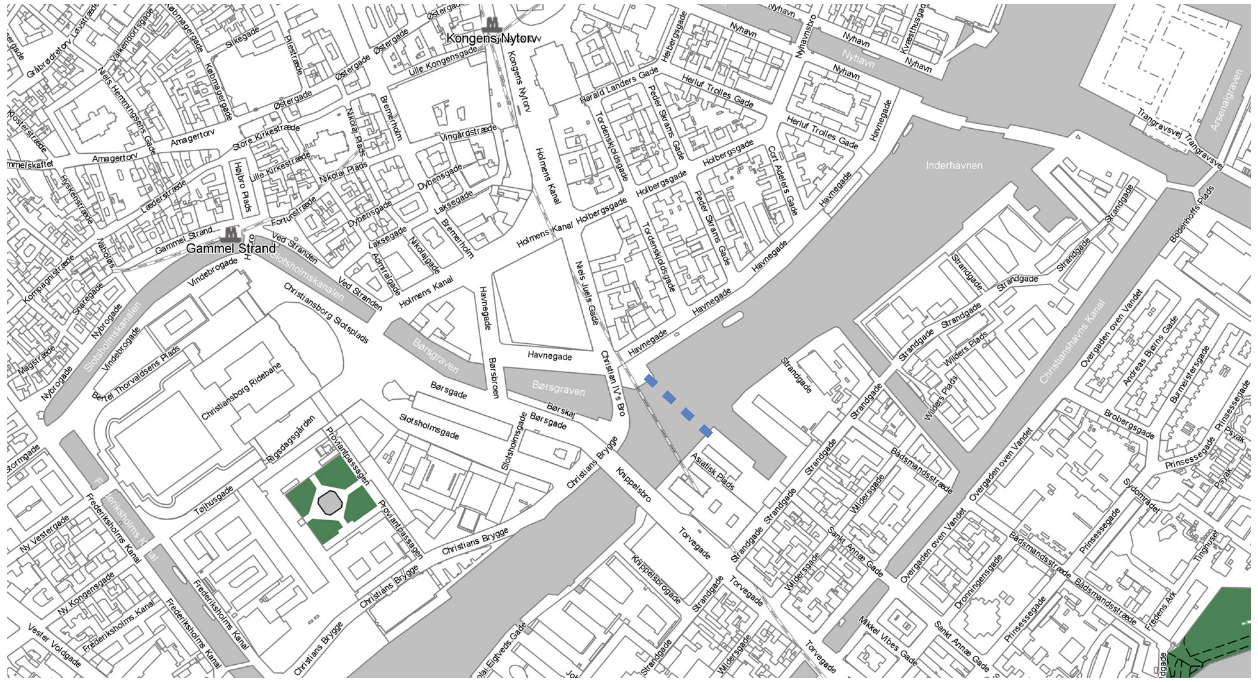
22 See Bicycle Strategy 2011-2025, https://civitas.eu/sites/default/files/documents/bicycle_strategy_2011-2025_copenhagen_0.pdf, 29.12.2020.

23 See Teglholmen, https://dac.dk/viden/arkitektur/teglholmen/, 5.6.2020.

24 See Copenhagen City Population, https://www.citypopulation.de/en/denmark/copenhagen/K04__vesterbro_kongens_enghave/, 5.6.2020.

25 See Copenhagen Green Accounts 2014, https://kk.sites.itera.dk/apps/kk_pub2/pdf/1393_bpsA36PvpI.pdf, 29.12.2020.





SITE C
HAVNEPROMENADE - ASIATISK PL.

The third site is located next to the Knippelsbro in the city centre. A footbridge in this location would offer commuters a safer, more attractive and car-free alternative to the Knippelsbro, which is currently the 2nd most used bridge crossing the port (for both cyclists and cars). The most used bridge is the Langebro (700m to the south) which received a replacement for bicycle and pedestrian traffic in 2019, the Lille Langebro. In the brief period since its opening in late 2019, it has already proven to be a valuable alternative for cyclists with over 10,000 daily users.[26]

In a case study on Copenhagen's congested bicycle traffic, which analysed the route choices of cyclists and their willingness to change routes based on traffic conditions, the authors concluded that many cyclists seem to be avoiding Knippelsbro and were diverting to the Inderhavnsbroen or the Langebro to avoid congestion.[27]

While a new bridge would certainly improve connectivity, it is unclear how much the overall travel time would be reduced. The problem of safety and congestion could potentially be solved by adapting the existing bridge or modifying the car traffic regime. Copenhagen has been steadily phasing out cars in the city centre over the decades and the Knippelsbro might see a reduction in car traffic in the near future.

26 See Lille Langebro, https://www.visitcopenhagen.com/copenhagen/planning/lille-langebro-gdk1111450, 21.5.2020.
27 See Mads Paulsen: Large-Scale Assignment of Congested Bicycle Traffic Using Speed Heterogeneous Agents, Jan 2019, https://www.researchgate.net/publication/333258472_Large-Scale_Assignment_of_Congested_Bicycle_Traffic_Using_Speed_Heterogeneous_Agents, 21.5.2020.


Sydhavnen 1945


Sydhavnen 2019

PROJECT SITE

Having assessed the arguments for each site, it was concluded that the most sensible location for the next major footbridge, the one that would benefit Copenhageners the most given current trends and circumstances, is the connection between Sydhavnen and the greener Amager Vest district. This decision was primarily based on the immediate need for a connection between a newly developed district and the east. The 2011-2025 Bicycle Strategy identified the area as problematic in terms of cycling infrastructure, with a need for large scale improvements, including several new bridges. Since the publication of the strategy, bridges have been built across the secondary harbours (Teglvaerksbroen and the Alfred Nobel bridge) but there is still a missing link to the east, over the main harbour. Many commuters travelling between east and west in the south are currently forced to choose between the relatively unsafe cycle route next to high-speed traffic over the Sjaellandsbroen or divert to the more bicycle friendly Bryggebroen more than 2.5 km to the north. A bridge in this area would give commuters and residents of these new developments a much faster, safer and more pleasant route through the protected Amager Natural Park.

KONGENS ENGHAVE DISTRICT

The King's meadow, better known as Sydhavnen (South harbour), is a rapidly developing district in southern Copenhagen. The decommissioning of the city walls in 1857 led to extensive industrial developments in the area. It is here that The Ford Motor Company established its first assembly plant on the European mainland, which opened in 1924. At the same time, residential buildings were erected to satisfy the need for workers' housing, which still characterises much of the district. During the plant's operation, Sydhavnen was a thriving area, but after the plant closed in 1965, most of the industry disappeared soon after. Over the next 20 years, Sydhavnen slowly gained a reputation for becoming the area with the lowest education rate and lowest life expectancy in Denmark.[28] In 1959, the long-awaited connection between Sydhavnen and Amager was established - Sjaellandsbroen. Part of the crossing initially included a 30 m bascule bridge, but due to the construction of the neighbouring fixed railway bridge in 1998, it is no longer movable. In 2020, a new master plan for Sydhavnen was developed as part of a collaboration between the City of Copenhagen, By & Havn and the architect Sjoerd Soeters. This ongoing redevelopment project has greatly increased real-estate prices and attracted new residents to the area. The areas receiving the most attention are the water-front peninsulas: Sluseholmen, Teglholmen and Enghave Brygge. Once finished, an area of approximately 120 hectares will offer nearly 5,000 residential units.[29] More than thirty architects and urban planners were involved in this redevelopment project. The Sluseholmen Canal District received the 2009 Danish Urban Planning award and has been recognised as one of the most successful new urban developments in Copenhagen. A new metro line due to open in 2024 (M4) will connect Sydhavnen with the north.

GREEN CYCLE ROUTES

The Green Cycle Routes are an important part of the city's transport system. They offer a pleasant alternative route to the busy road cycle paths, especially during peak hours.[30] There are currently 58km of Green Cycle Routes and more are planned for the future. Among the planned routes is a path leading through the Teglholmen peninsula that will cross over to the Amager Nature Park where it will merge with the existing paths.

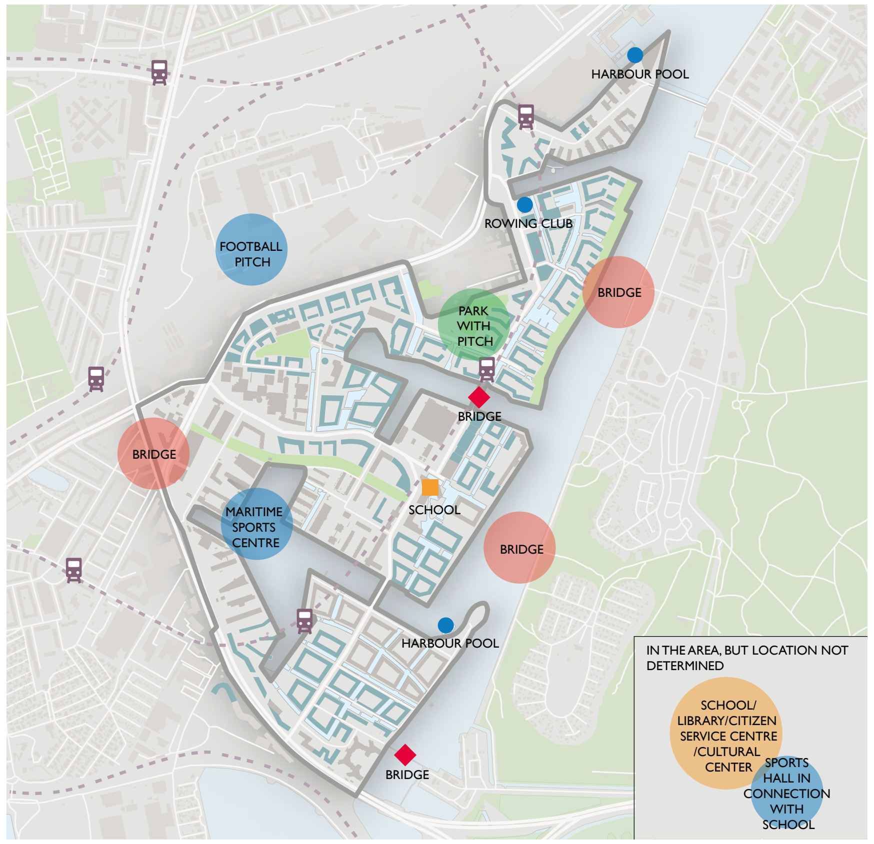
28 See Stig Orskov: Udstødningshavnen, 21.6.2000, https://www.information.dk/2000/06/udstoedningshavnen, 8.6.2020.
29 See John Pendlebury, Heritage, urban regeneration and place-making, 2.6.2017, https://www.tandfonline.com/doi/full/10.1080/13574809.2017.1326712, 29.12.2020.
30 See CSGN Green Cycle Routes, http://centralscotlandgreennetwork.org/resources/publications/category/116-green-active-travel-route-case-studies?download=412:green-active-travel-green-cycle-routes-copenhagen, 29.12.2020.

Graphic from the Local plan 310-11

Development plan

2-3 storey Buildings
3-4 storey Buildings
4-5 storey Buildings
1-6 storey Buildings
5-6 storey Buildings
5-7 storey Buildings

Penthouse
Trees
Road bridges
Footbridges
Staircase
Moveable footbridges



Existing buildings
Planned or funded buildings
Green areas open to the public
Existing or funded school
Existing or funded sports facility
Existing or funded bridge/ tunnel
Proposed school
Proposed sports facility
Proposed park
Proposed bridge/tunnel

Graphic from the Municipal plan 2015

MASTERPLAN TEGLHOLMEN

This part of the South Harbour has been planned as a canal-side community with a focus on creating a coherent area with bridges, closeness to public transport and good connections for cyclists and pedestrians. It is a mixed residential and commercial area with a number of functions, including retail, day care, educational and recreational facilities. The development is built around the canals and a harbour basin. The harbour basin is strategically located in the middle of the peninsula where the 750 m long green belt passes the school. This green belt connects the main residential area at the harbour front with the Sydhavnen Station. The local municipal plan also proposed a cycle and footpath connection from Teglholmen to Amager via a footbridge as an extension of the green belt.[31] The harbour activities are being moved further north to a new and bigger port while the south harbour is becoming increasingly redundant.[32] In the urban development strategy, the goal for the transformation of the area is to create a new functional urban district of a high standard with a family-friendly living environment into which business, cultural, public and audience-oriented functions are integrated. It also aims to draw water into the area, thus creating a unique environment that will be attractive both locally and across the whole city.

The main connectivity routes are the boulevard from Havneholmen in the north to Sluseholmen in the south, which links the new urban areas via bridges over Teglvaerksløbet and Frederiksholmsløbet, and the green cycle route network which will include new footbridges over the harbour and connect the urban areas with green areas in Amager.

31 See Municipal Plan 2015, https://kp15.kk.dk/artikel/municipal-plan-2015, 29.12.2020.
32 See Sjoerd Soeters: Sydhavnen/Sluseholmen Copenhagen Harbour renovation project 2000-2009, https://pphp.nl/wp-content/uploads/2017/05/SLUSEHOLMEN.pdf, 29.12.2020.

Maori ceremonial fishing hook, Knight Architects, Lower Hatea River Crossing, New Zealand

III. DESIGN AIMS AND CONSTRAINTS

Port life is an important element of Copenhagen's identity and urban life. However, the harbour is both a connection for the sailors and a barrier between the districts. The bridges over the city's waters must contribute to the goals of developing urban life and the city's physical contexts along and across the harbour.[33] A footbridge should of course primarily be functional but, in addition to connecting separated spaces, it also provides the opportunity to build new public spaces and give an area its own identity. The site's topography, wider context and unique features have to be considered. The CROW institute from the Netherlands has formulated a set of criteria for designing cycling infrastructure that can also be used as guidelines for footbridge design in general.[34] These requirements are:

Cohesion
Directness
Attractiveness
Safety
Comfort

These traffic related requirements can be further extended to include spatial requirements such as:[35]

Spatial integration
The user's experience
Socio-economic value

MOVABLE BRIDGE

A bridge over the port of Copenhagen needs to be movable in order to grant passage to larger vessels. An opening mechanism adds considerable complexity to a project and often dictates the overall design of a bridge. Compared to fixed bridges, movable bridges have a greater number of delicate components which are prone to failure, require more maintenance and significantly add to the cost of the structure. There are a limited number of options for opening mechanisms which are efficient: these usually require a counterweight to keep the forces needed to open the bridge as low as possible. Each movable bridge type has its own advantages and disadvantages in terms of efficiency and fit to the site. Whilst this may seem like a design constraint, there is room for innovative execution of these options. In some cases it may be possible to take advantage of this constraint and incorporate the movable mechanism into the overall design and make it part of the identity of a bridge or a place. An example worth noting is the Lower Hatea Crossing in New Zealand. The inspiration for the geometry of the rolling bascule was the shape of the ceremonial fishing hook used by the indigenous Maori tribes. The design successfully combines functionality and local identity with a simple yet expressive bascule.

33 See Administrationsgrundlag for broåbning, http://kk.sites.itera.dk/apps/kk_pub2/pdf/1280_yFF4l4mvFl.pdf, 29.12.2020.
34 See Bendiks/Degros 2013, 18.
35 Ibid., 20.

However, innovation for the sake of innovation often leads to designs that are out of place and require more maintenance than necessary. A prominent example of this is the Inderhavnsbroen. The complexity of the retractable mechanism, which was the driving concept behind the design, resulted in major delays during construction, additional costs and decreased safety for its users.

BRIDGE OPENING

In 2011, the city of Copenhagen established an administrative basis for bridge opening with the goal of creating a better connection between urban and harbour life. This aims to balance the interests of sailors, cyclists, pedestrians and motorists with frequent and efficient bridge openings. Different parts of the harbour have different characters in relation to their pattern of use. Based on an assessment of closing times and opening hours, the bridges can be divided into two categories: main port bridges and secondary stream footbridges. The former are essential connections to the city's overall infrastructure and are therefore less flexible in terms of opening. Conversely, in the secondary streams the bicycle and pedestrian bridges will open more often. They are important connections in the city but, because they do not contain motor traffic, are far more flexible in relation to openings. Bridge openings are generally free of charge during regular schedules but can be requested to open on special occasions for a fee.

Most main port bridges have a vertical clearance of 5.40 m over mean sea level to allow the passage of smaller boats. The exceptions are the final three bridges in the harbour - Teglværksbroen, Sjællandsbroen and the adjacent railway bridge. All of which have 3 m vertical clearance. The journey for larger boats ends with the Sjællandsbroen in the south. This bridge used to have an opening bascule section but this was permanently closed after the construction of the adjacent railway bridge in 1998. Statistics from 2009 show that on average, each bridge was opened once every other day with the outer bridges opening more often than the inner bridges.[36]

Secondary stream bridges are more flexible in terms of vertical clearance because they can be opened more frequently without substantially disturbing traffic. Their passing width also depends on the context. Most secondary bridges have a vertical clearance of around 2.30 m and 15 m passing width.[37] Bridge opening should also cause as little disruption to regular traffic as possible. Bridges in Copenhagen have opening times scheduled outside of peak hours and are kept as short as possible. However, on some occasions the bridge has to be opened during rush hour. To alleviate disruptions to traffic, proper signalling and notification of closure must be in place. This can be achieved by notifying users about the closures in advance by placing digital schedules in eye-catching locations near the bridge. Users can then plan their journeys or choose an alternative route.

The passing width requirements depend on the location. The Inderhavnsbroen, which is the first in the series of bridges over the main harbour, has a passing width of 45 m; the Knippelsbro, Langebro, Lille Langebro and the Bryggebroen all have 35 m. The Teglværksbroen has 15 m of navigable width and the width of the Slusen lock further south is 10m.

According to Local plan 310, the proposed bridge between Teglholmen and Amager must have a 25 m wide opening segment; however, the plan does not specify the passage requirement

36 See Administrationsgrundlag for broåbning, http://kk.sites.itera.dk/apps/kk_pub2/pdf/1280_yFF4l4mvFI.pdf, 29.12.2020.
37 Ibid., 42-44.

Nautical map showing navigation channels

for the closed condition.[38] Nevertheless, it can be assumed that the clearance envelope of the new bridge should be no lower than that of the neighbouring Bryggebroen, which is 19 m wide and 5.4 m high.

The opening of a bridge is often a spectacle that draws the attention of tourists and passers-by. In places where people will watch bridge openings on a regular basis, a bridge designer should look beyond its practicality. There are several examples of bridges where people intentionally visit in order to view its opening. Such bridges can add to the cultural or even economic value of a place and transcend their main function. In such cases, higher construction costs can be justified provided they do not impede maintainability or add unnecessary complications. In most cases, a design should refrain from being innovative for the sake of innovation.

NAVIGATION CHANNEL

The marine navigation channels at the project site between Amager and Teglholmen pose several challenges for bridge design as there are two separate navigation channels and a shallow area in between. It will be necessary to balance cyclists' need for a comfortable crossing with ensuring the navigability of the harbour.

The Copenhagen Harbour Bus network consists of three bus routes with a total of 10 different bus stops along the harbour front. The harbour buses 991 and 992 connect Refshaleøen in the north with Teglholmen in the south, with the final stop next to the Teglværks bridge. The new electric powered boats introduced in January 2020 can carry up to 80 passengers and sail every 30 minutes. The boats are 5.6 m wide and require a vertical clearance of 5.4 m above mean sea level. They transport approximately 425,000 passengers annually.[39]

The city of Copenhagen has been promoting bicycles as a primary mode of transportation for several decades, which has resulted in large scale changes in infrastructure, both on land and on water. New bridges should be designed in a way that prioritises bicycle users, which means that the slope of the crossing cannot be steeper than is reasonably comfortable for the average user. To keep the harbour navigable for large vessels, as well as stay within the slope constraints for the bridge, two possible solutions have been explored:

1. Reducing navigation clearance

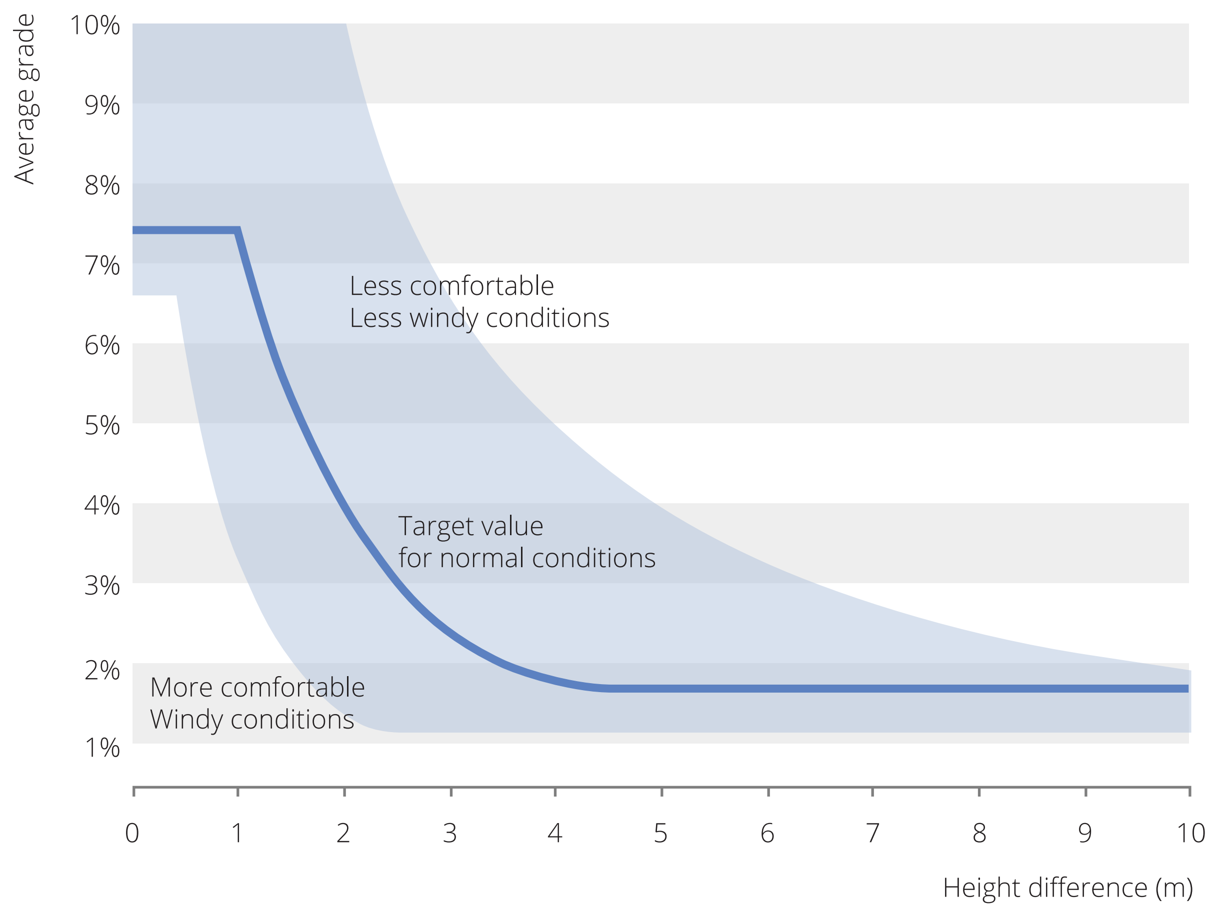
The project site is located almost at the end of the harbour, where the journey for vessels higher than 3 m ends. Reducing the clearance envelope from 5.4 m to 3 m, means that the final water bus station would have to be relocated to the nearest possible site where there are no such height restrictions. This would mean that the journey of some passengers would be extended by at least 450m. This approach would still require two separate opening spans to cover both navigation channels. Both would have to be kept to a minimum of 15 m to maximize the opening speed and enable large vessels to pass more frequently without causing too much inconvenience for cyclists. There are only a few examples of movable bridges with two separate opening spans due to increased start up and maintenance costs.

2. Dredging

A possible solution for this kind of dilemma is to widen or merge the existing navigation channels by dredging. This would result in one navigation channel in the middle where the clearance

38 See Local plan 310, https://blivhoert.kk.dk/hoering/teglvaerkshavnen-tillaeg-11-lokalplan-310-11, 29.12.2020.

39 See New harbour buses, https://www.kk.dk/sites/default/files/uploaded-files/movia_-_presse_og_nyheder.pdf, 29.12.2020.



envelope under the bridge can be at its highest. The channel would then split further south. In this case, only one opening span would be necessary, substantially reducing the complexity, start-up costs and maintenance costs of the bridge. Other benefits of this approach would be increased height clearance, ensuring the water bus route remains unchanged, and the distancing of marine traffic from the waterfront residential developments.

SEGREGATION

Clear segregation of cycle and pedestrian traffic is often one of the most desirable features of a footbridge. Mixing different traffic groups without clear separation causes frustration and can lead to accidents. These risks are often amplified on bridges as people generally feel less secure. Good design helps to mitigate these risks by introducing various measures such as height variation, colour variation, physical barriers and proper paving materials.

SPATIAL REQUIREMENTS

In Copenhagen, bicycles come in many different shapes and sizes. Cargo bikes are a common method for transporting goods as well as small children.[40] It is important to take other forms of bicycles into consideration when determining the dimensions of cycling lanes on a bridge. In order for all users to safely use the bridge, general factors such as slopes, widths and curvature, as well as location-specific factors must be carefully evaluated.

Slope

In general, the difficulty of a ramp for cyclists depends on a combination of its grade and length, but it also depends on the different types of users. Although steep slopes should be avoided wherever possible, they are sometimes inevitable due to vertical clearance requirements for the traffic below the bridge. The difficulty of the ramp (Z) can be calculated using the following formula.[41]

$$Z = (\text{height difference [m]})^2 / \text{length}$$

This formula shows that a 125 m long ramp with a rise of 5 m has the same difficulty as a 31 m long ramp with a 2.50 m rise. For a ramp to be reasonably comfortable, the Z value should not exceed 0.2 with a maximum grade of 10%.

The Danish bridge design guidelines recommend that the maximum slope in the longitudinal direction should not exceed 4.5%.[42] The local plan 310 specifies a maximum slope of 5% for the proposed footbridge connecting Teglholmen and Amager.[43]

Clever solutions can be introduced to reduce the angle of inclination by properly aligning the structural system with the desired vertical clearance envelopes. Sudden changes in slope grade should be avoided and the transition between the sloping and flat sections should be as smooth as possible. Cyclists also lose speed moving uphill which makes it more difficult for them to ascend. Ideally, the grade should reduce gradually towards the top. Cyclists should also have a clear view of the ramp so they can anticipate the effort needed to climb it and possibly increase their speed at the start.

Width

The width requirements for a footbridge are based on a variety of factors. Firstly, user groups and their expected counts have to be

40 See 2018 Bicycle Account, https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1962, 29.12.2020.
41 See Van Den Berg 2015, 26-27.
42 See Danish guidelines for bridges, https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1461, 29.12.2020.
43 See Local plan 310, https://blivhoert.kk.dk/hoering/teglvaerkshavnen-tillaeg-11-lokalplan-310-11, 29.12.2020.

Epoxy bound aggregate surfacing

determined. The city of Copenhagen regularly publishes bicycle and motor traffic counts that indicate a growing number of daily bicycle users on all bridges. Although there are no published counts for pedestrians, surveys indicate that on average people will only walk to work or school if the destination is less than 1 km from their home.[44] Given that the bridge will connect a residential district with a large natural reserve, it can be assumed that most pedestrians will be local residents using the bridge for recreational purposes. Recreational users are usually not concerned with getting to their destination on time and their speed is lower compared to commuters. This presents an opportunity for the footbridge to change from a route to a destination.

In general, the minimum width between the railings for a two-way cycling path should be 2.40 m. Safety margins such as steep slopes, curved plan alignments or raised pavements can increase the minimum requirements. Small children and the elderly tend to swerve more when cycling uphill. In areas with nearby schools or retirement homes, a safety margin of 0.50 m to the bridge width should therefore be added.

The local plan 310 for Teglholmen specifies that the new bridge should be approximately the same width as the Bryggebroen, which is 3 m for cyclists and 2.5 m for pedestrians.[45] These values should serve only as guidance and ideally should be higher.

DECK SURFACE

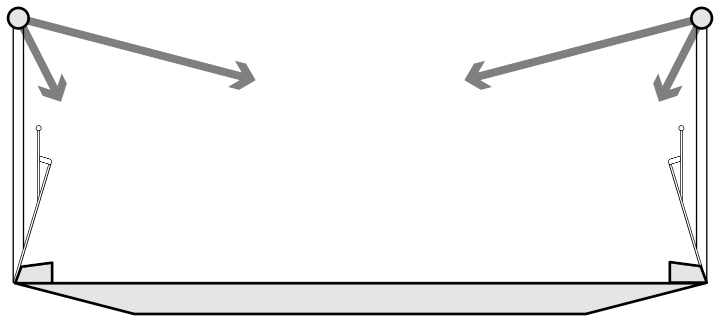
After the spatial requirements have been determined, an equally important factor for safety and comfort is the deck surface. The most common types of bicycle used by Copenhageners are utility bicycles, which have little or no dampening and fewer gears. They are not designed for speed or efficiency. To give users the maximum riding comfort, which encourages more people to use bicycles regularly, the surfaces on which they ride should be as smooth as possible, as well as supplying sufficient grip which is especially necessary in wet conditions on curves and slopes. The decking surface also has to be durable and easy to maintain. There are many decking surface solutions on the market, each with different properties and for different applications. Permeable asphalt is a common solution due to its drainage properties and grip but may be undesirable if weight is an issue. Other possible solutions include concrete surface treatments, resin bound aggregates and various coatings.

PARAPETS

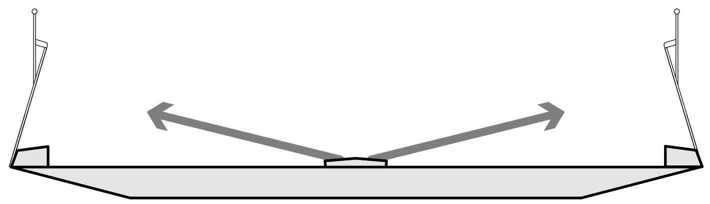
Parapets are an essential component on all footbridges. Primarily, they protect people from falling and are required to withstand certain horizontal loads in case of impact. They are also used as guidance for the visually impaired and assistance for the elderly and physically impaired. In addition to a specific minimum height and other safety requirements, they also have to provide users with a visual sense of safety. Parapets can be part of the load bearing structure but are more often designed as a separate element.

Parapets influence the architectural presence of a footbridge to a much greater extent than on road bridges. For pedestrians, parapets are the main architectural element they observe and come into physical contact with, especially bridges where the rest of the structure is below the deck and out of sight. It is therefore essential to pay special attention to the materials and finish quality. Parapets should also be designed in accordance with the overall concept of a bridge design.

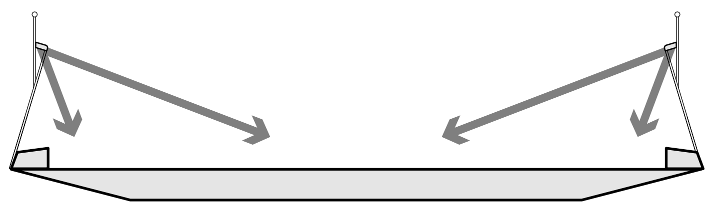
44 See Larsen, Marie K., 2010, https://www.trafikdage.dk/papers_2010/406_MarieKLarsen.pdf, 29.12.2020.
45 See Local plan 310, https://blivhoert.kk.dk/hoering/teglvaerkshavnen-tillaeg-11-lokalplan-310-11, 29.12.2020.



Lamp posts



Lamps at ground level



Lamps integrated in railing

The most important safety factors for parapets are structural integrity, height and the space between individual elements. The minimum height of railings for bridges with cyclists in most European countries lies between 1.20 m and 1.30 m, which is the centre of gravity of an average cyclist. In such cases, additional railings for pedestrians at an appropriate height – 0.85 m – 1.00 m should be considered.

There are countless possible designs for parapet infill. The most common are vertical and horizontal posts, wire meshes and solid closed elements. The choice for a particular parapet type depends on its fit with the overall design, the desired appearance from different angles, and budget. The infill must be designed in such a way as to prevent climbing and slipping through the individual elements. For vertical infill rods, the distance between the rods should be less than 12 cm. This will prevent even small children from getting their heads stuck between the posts. Horizontal elements should be inclined inwards or have an overhanging handrail while wire meshes should have a maximum opening of 60 x 40 cm to prevent climbing.[46]

LIGHTING CONCEPT

The illumination on footbridges has multiple functions. Its primary objective is to safely guide users across the bridge but it should also emphasise and call attention to the structure's presence as part of a specific local identity within an urban context. A luminaire consists of three main parts: an illuminant, a reflector and casing.[47] The range of possible configurations is enormous. Common types used on footbridges are light posts, ground level lighting and handrail lighting. The choice of configuration depends on the primary lighting purpose and the desired lighting effect. Protection from weather and vandalism also has to be considered, which may limit the choice. For clear guidance along a path, certain light uniformity is required. This may vary for different user groups. Cyclists move at higher speeds and have less time to react to possible debris. They therefore require a more homogeneous illumination than pedestrians who move at a third of their speed. LED strips or other forms of continuous light bands, either at ground level or integrated into railings, provide great uniformity. Replacing failed sections of LED strips is also much more difficult than replacing single lighting elements such as spotlights. The authorities responsible for the maintenance of a bridge do not usually go through the financial inconvenience of replacing single failed sections, which gives a strong appearance of negligence. A successful and durable lighting concept requires cooperation between the architect and a specialised lighting designer. For a bridge running through a residential area, the direction of luminaires has to be carefully studied to ensure there is no unwanted light spill towards the living spaces. Light temperature and colour also play a critical role. Depending on the location, colour lighting may be required to confer a special identity on a place. For increased visibility of footpaths and cycleways, warm-white to neutral-white (3000K - 4000K) path illumination is preferable.[48]

LOADS

According to EN 1991-2 and the Danish national annex, a footbridge must uniformly withstand distributed vertical loads of 5kN/ m². In addition to these loads, a footbridge must be dimensioned for a service vehicle weighing 5 tonnes with a 3 or 2 axle configuration, as specified in the national guidelines for bridges. The recommended snow load value for Copenhagen is 1kN/m².

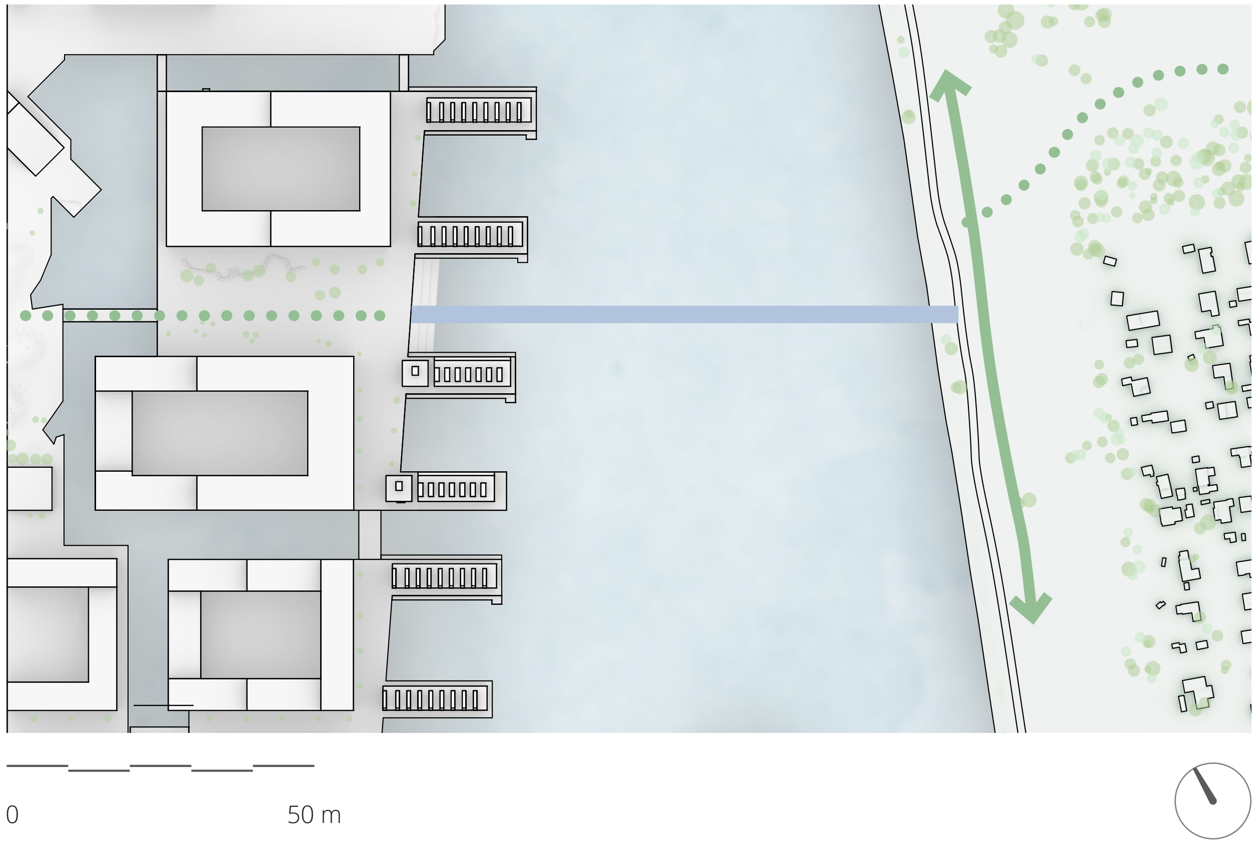
46 See Keil 2013, 14.
47 Ibid., 74.
48 See FIB 2005, 77.

IV. **PROJECT**

Copenhagen is one of the most bicycle friendly cities in Europe. It earned this title after decades spent prioritising bicycles as the preferred transportation method and constructing its infrastructure projects around this principle. Some of the recently built bridges, such as the Bicycle Snake and the Lille Langebro, have become icons of the city's bicycle culture. Their success can be attributed to the architects' understanding of users' needs, careful study of the wider context in which the bridge is placed and the clarity of thought behind every design decision. Some bridges are sophisticated because of their complexity while others are simple and straightforward yet elegant. Understanding the key success factors underpinning these projects, as well as missteps like the Inderhavnsbroen, can help guide future bridge projects in a positive direction.

With 12 new bridges built over the past 6 years, it is pertinent to ask the question; does the city need another bridge? Copenhagen is a growing city. With entire artificial islands being constructed in the north and former industrial districts being re-developed in the south, numerous opportunities remain for ambitious spans over the harbour. One of these potential sites is the proposed connection between the newly constructed residential islet - Teglholmen and Amager Natural Park. The aim of this project is to respond to the design constraints described in previous chapters and design a harmonious connection across the harbour. The design choices were made by carefully analysing the constraints and employing them in favour of the design, rather than simply striving to overcome them.

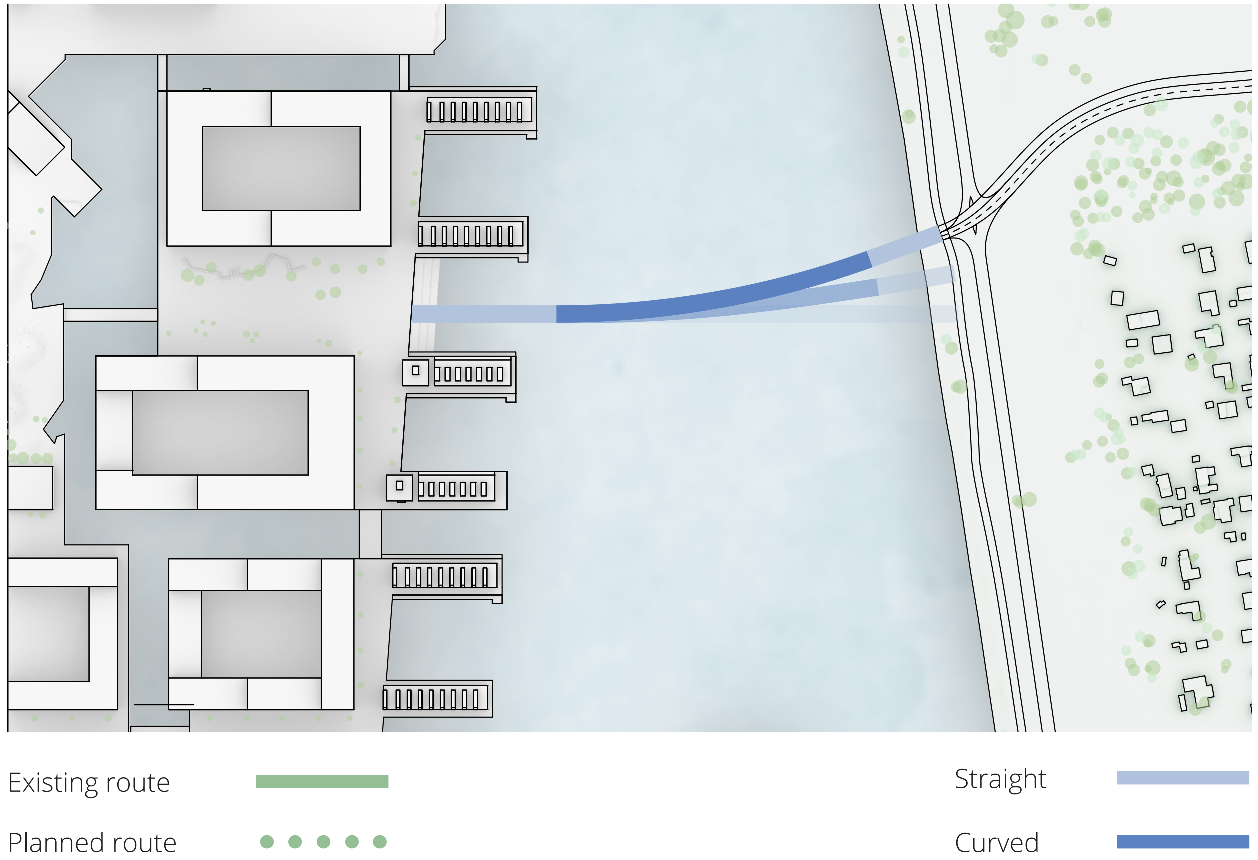
The project thus aims to create a highly functional and attractive crossing that responds naturally to the limitations and characteristics of its surroundings. The driving concept is based around the interweaving of the design constraints and adaptations to the peculiarities of the site.

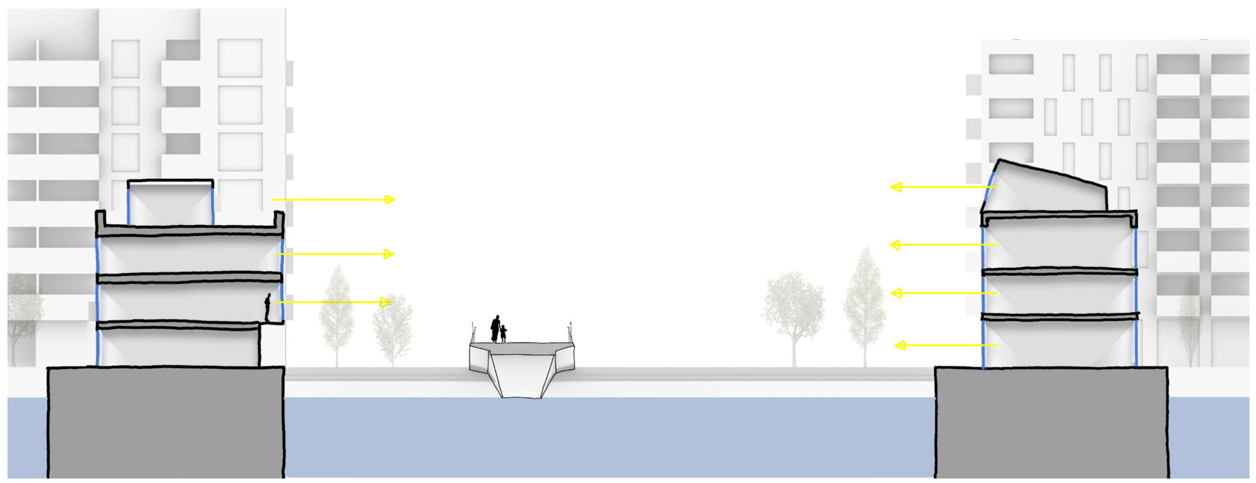


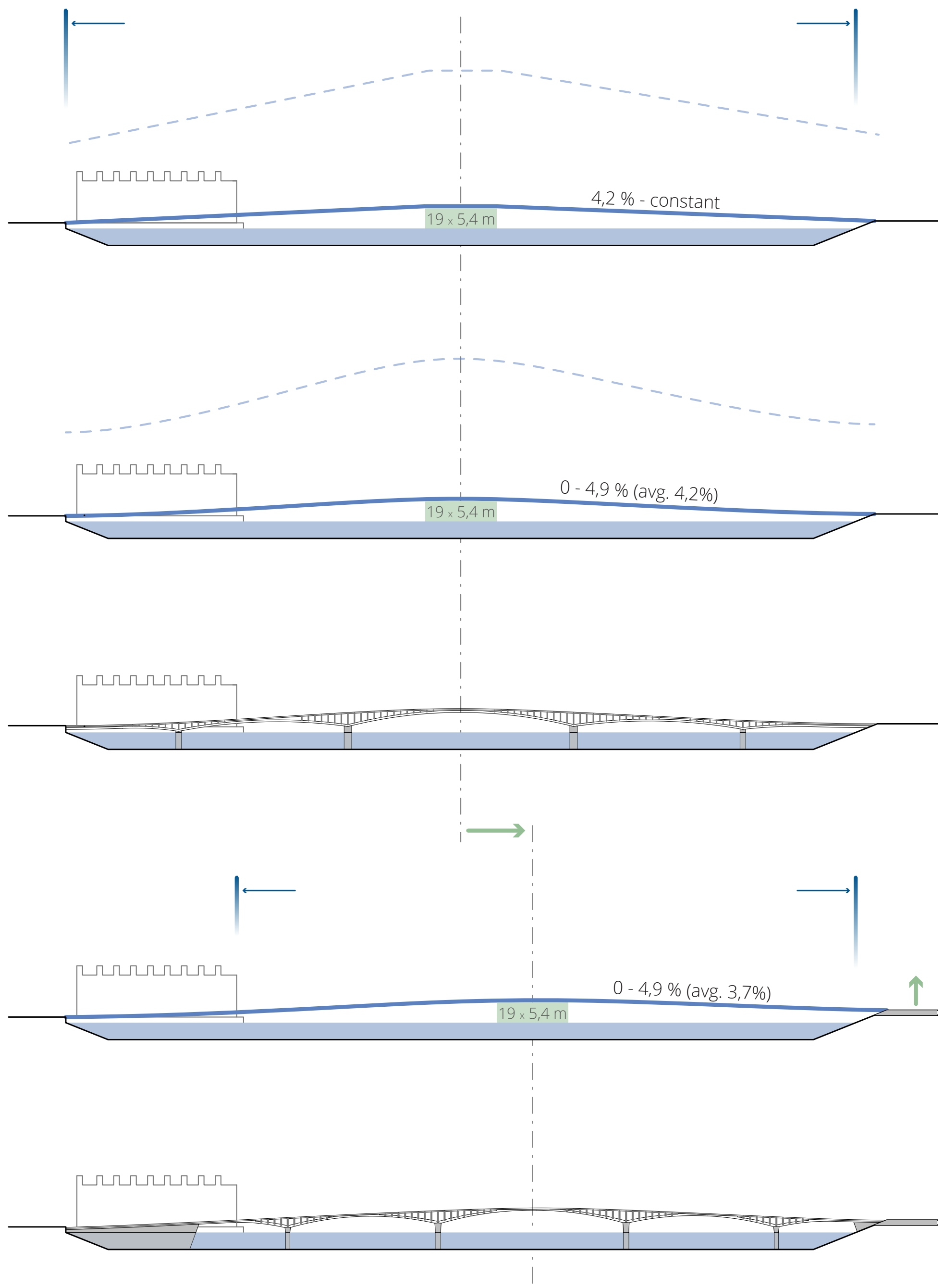
HORIZONTAL ALIGNMENT

As well as having a different topology, the embankments also differ in terms of the direction of the routes. The dominant route on the east (Amager) side is currently the north-south direction, which links the inner city with the outskirts while the planned route through the Amager Natural Park will connect the eastern periphery with the harbour. The master planners of Teglholmen laid the foundation for a west-east connection by emphasising the axis that starts at the South Harbour station and cuts through the middle of the peninsula in the form of a 700 m long and 40 m wide green wedge with footpaths and cycle routes.

To effectively close the gap between both routes, the bridge axis has to be adjusted accordingly. On the Teglholmen side, where the route passes between the houses on the waterfront, the axis remains parallel to the buildings and is then slightly bent so that it becomes aligned with the new route leading through the Amager Natural Park. The landing site on the west bank is deliberately placed closer to the south building for two reasons. Firstly, this alignment matches the existing travel axis through Teglholmen. Secondly, the two buildings facing the bridge differ in their relation to the outside world. While the ground floor of the south building only serves as an entryway to individual apartments, the north building has terraces and large windows facing the bridge. For the purpose of maintaining the privacy of the residents and counterbalancing the different vantage points, an eccentric bridge alignment was chosen.

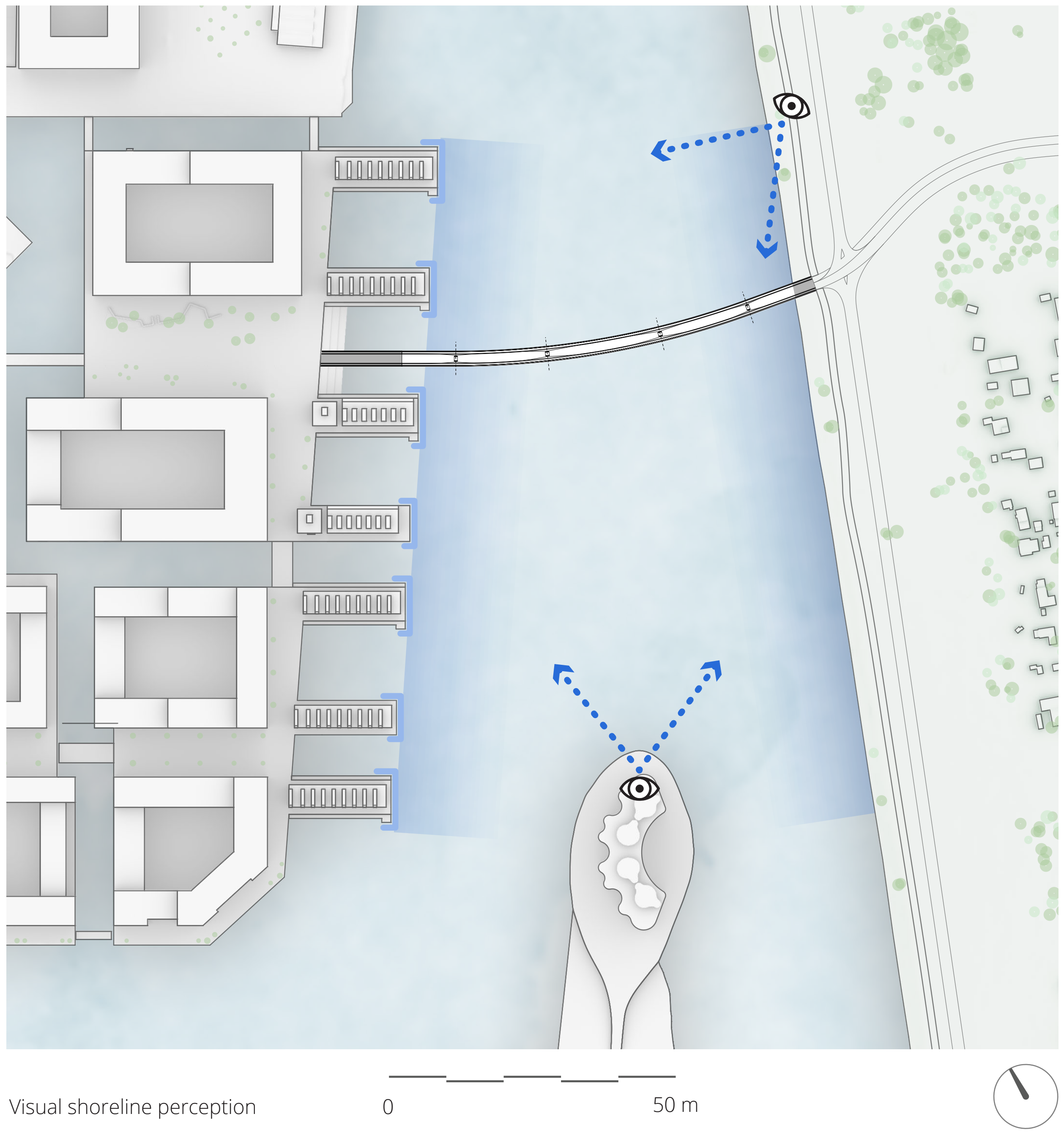






VERTICAL ALIGNMENT

One of the main challenges bridging the harbour on this particular site is to overcome the navigation height clearance while remaining within the comfortable cycling gradient range and maintaining a visually well-proportioned structure. Assuming a deck height of 0.50 m, a minimum gradient of 4.2% is necessary to overcome the 19 x 5.40 m clearance envelope over the entire 220m crossing. However, this is undesirable for various reasons. A well-integrated cycling bridge should aim to make the transition from land to bridge as smooth as possible. This means that a gradient that steadily ramps up over a set distance is preferable to a sudden change in inclination. For cyclists, this means they have to maintain the maximum effort for a shorter distance and can increase their velocity prior to the climb in order to gain momentum.

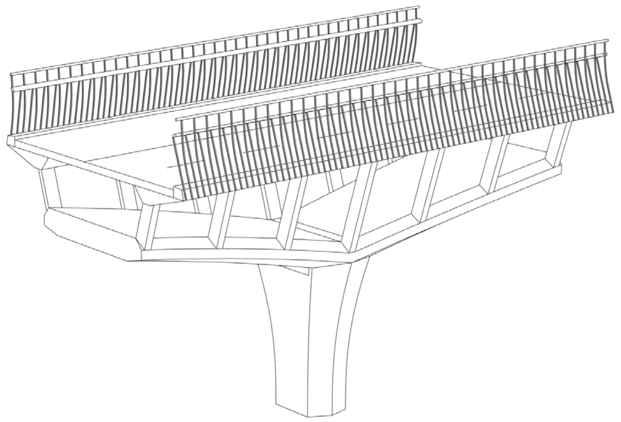


Visual shoreline perception

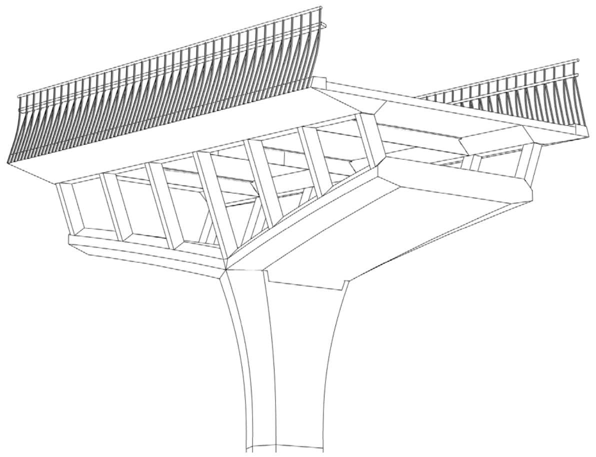
Another peculiarity of the site is the perception of a false shoreline created by the buildings on the harbour front. An observer travelling along the harbour will thus perceive the width of the harbour as different to its actual width due to the obstructed view of these buildings. This presents an opportunity to shift the peak of the bridge away from the buildings which brings further benefits as well as new challenges. Shifting the apex of the bridge away from the middle would normally mean an increase in the maximum gradient of the ramp on the shorter side. However, the embankment on the Amager side has the advantage of being able to adapt the landscape to the bridge, while the height of the landing in Teglholmen is fixed. The structure on the west side begins as a solid 35 m long ramp, which compensates for the shift of the apex and pushes the main structure towards the false shoreline created by the buildings.

The architectural language of the footbridge is characterised by the interplay of arched and linear elements on multiple levels. On a macro level, it is expressed through the shape of the horizontal alignment, as well as its elevation. On a more personal level, the user experiences this interplay by coming into contact with the parapets.

The steel-concrete composite deck is supported by a steel substructure consisting of an arched bottom chord and equally spaced inclined verticals. This array of vertical elements reflects the jagged roof shapes that characterise the harbour-front buildings. Their hexagonal cross section gives the overall substructure a more slender and elegant appearance.



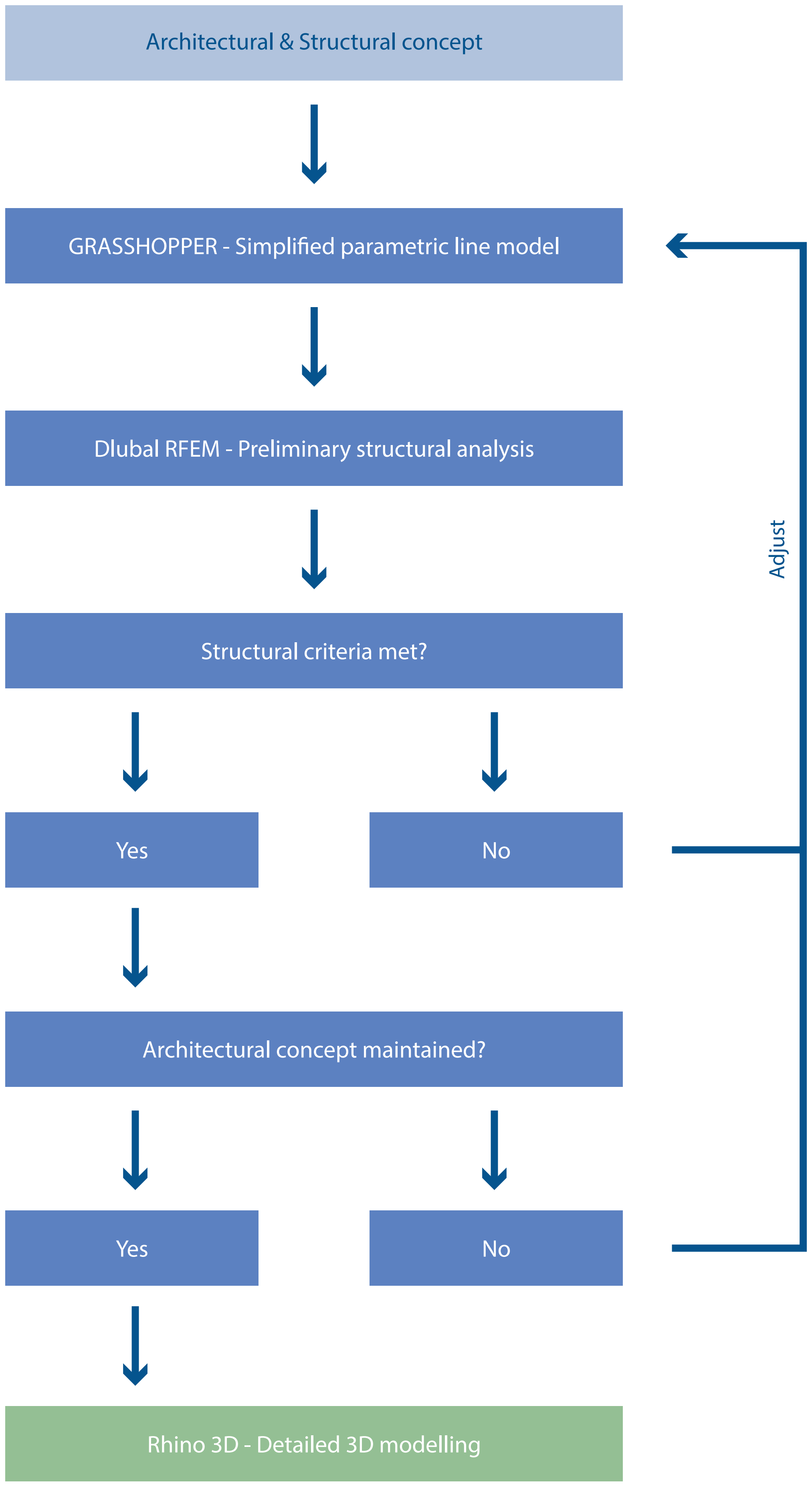
3D View



3D View

The height of the bottom chord steel girder varies from 40 cm at mid span to 65 cm at the supports. This variation in height is the result of a preliminary structural analysis which demands a stronger structure towards the piers. The changes in height also present an opportunity to introduce additional creases into the soffit, which break up the uniformity of this large surface. The creases of the bottom chord steelwork are carried over to the supporting concrete piers.

The bicycle and pedestrian lanes are clearly distinguished through the use of different colour tones of the non-slip epoxy bound aggregate surfacing.



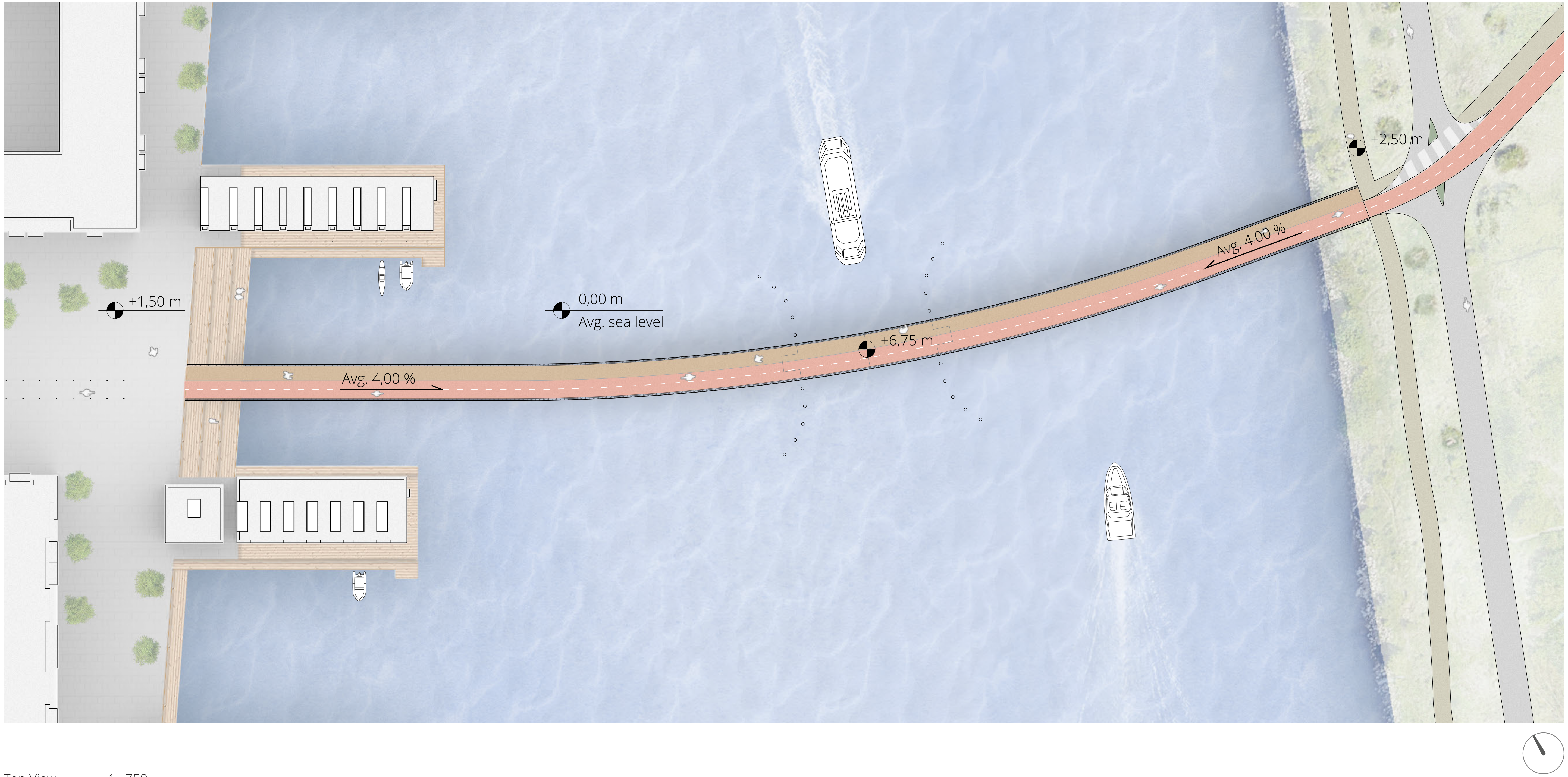
Workflow

FORM FINDING

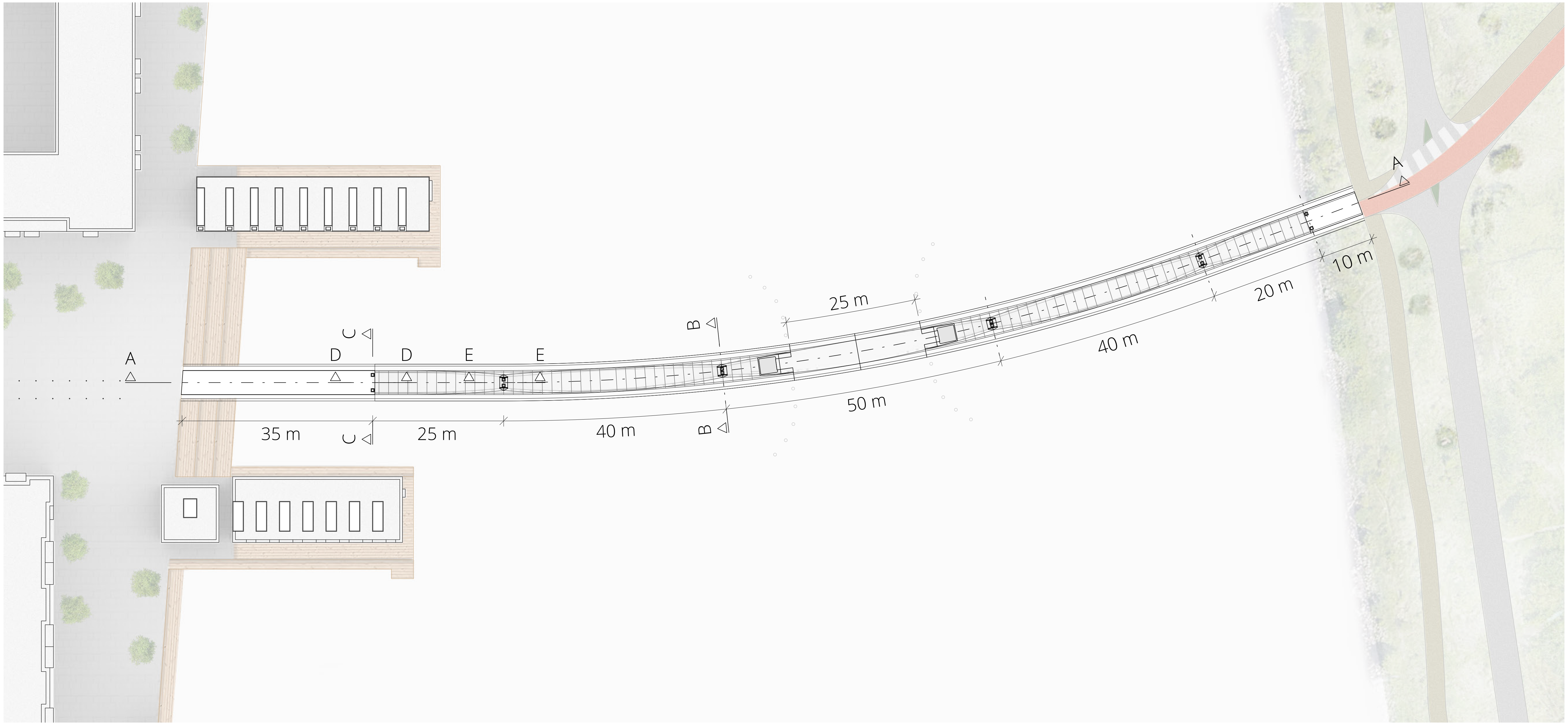
After deciding on an overarching design concept, a preliminary structural analysis was conducted to optimise the size and shape of the structural elements. The serviceability criteria for the maximum deformation were set to L/800 while the main structure material was set to steel grade S355.

The software employed for the analysis and optimisation was Dlubal RFEM 5.23 in combination with a live-link to Rhino 6 and Grasshopper. Firstly, a simplified parametric grasshopper line model was created which enabled fast adjustments of parameters such as span length, structure height, element spacing and cross section geometry. This model was then linked directly to the Finite Elements Program - Dlubal RFEM - where load cases were defined and, finally, the structural analysis was calculated. The results were local deflections and internal stresses of individual elements. The resulting values highlighted problematic areas where the initial parameters had to be adjusted in order to meet the serviceability criteria and enable the cross-sections to withstand the stresses. Support reactions were also used to determine the size of support bearings.

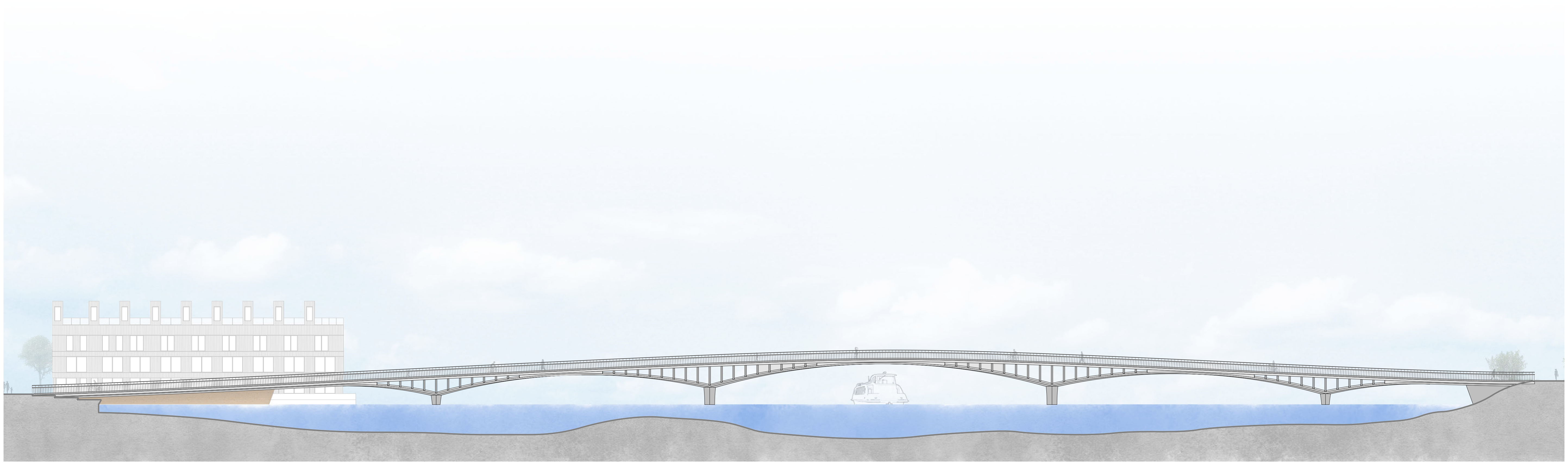
After several iterations, a form was found that met the SLS deformation criteria of L/800 and where the ULS stresses of all members were below the material's yield strength. The structural model was then carefully evaluated in terms of its conformity to the overarching architectural concept, which led to fine adjustment of the steelwork without fundamentally changing the load bearing structure.



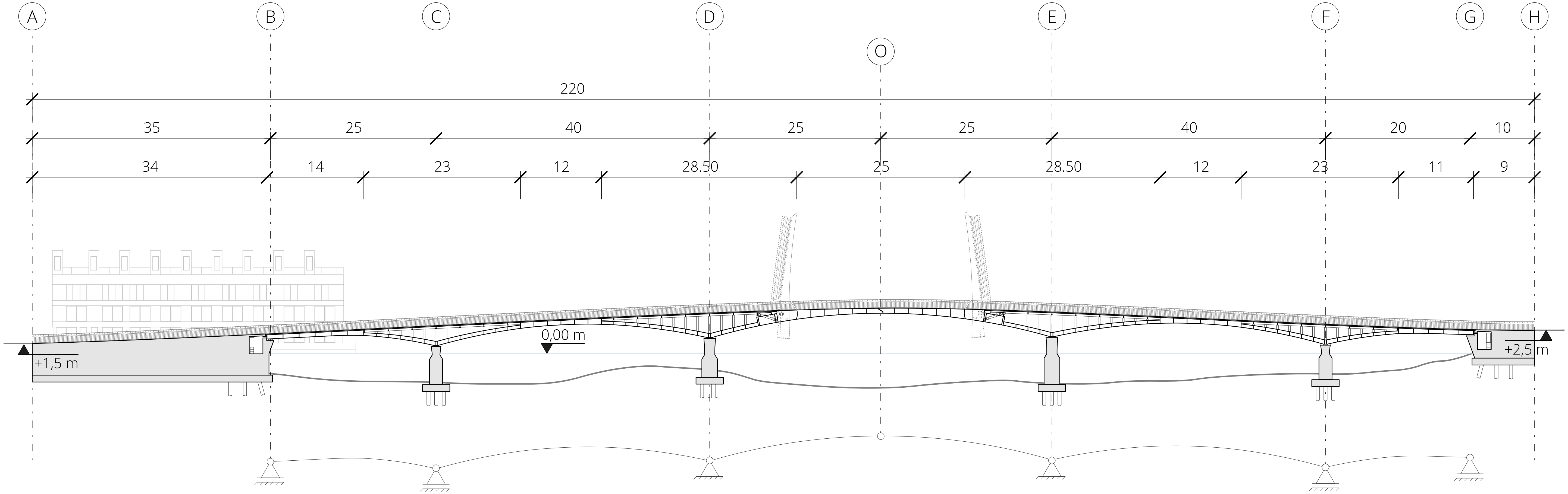
Top View 1 : 750



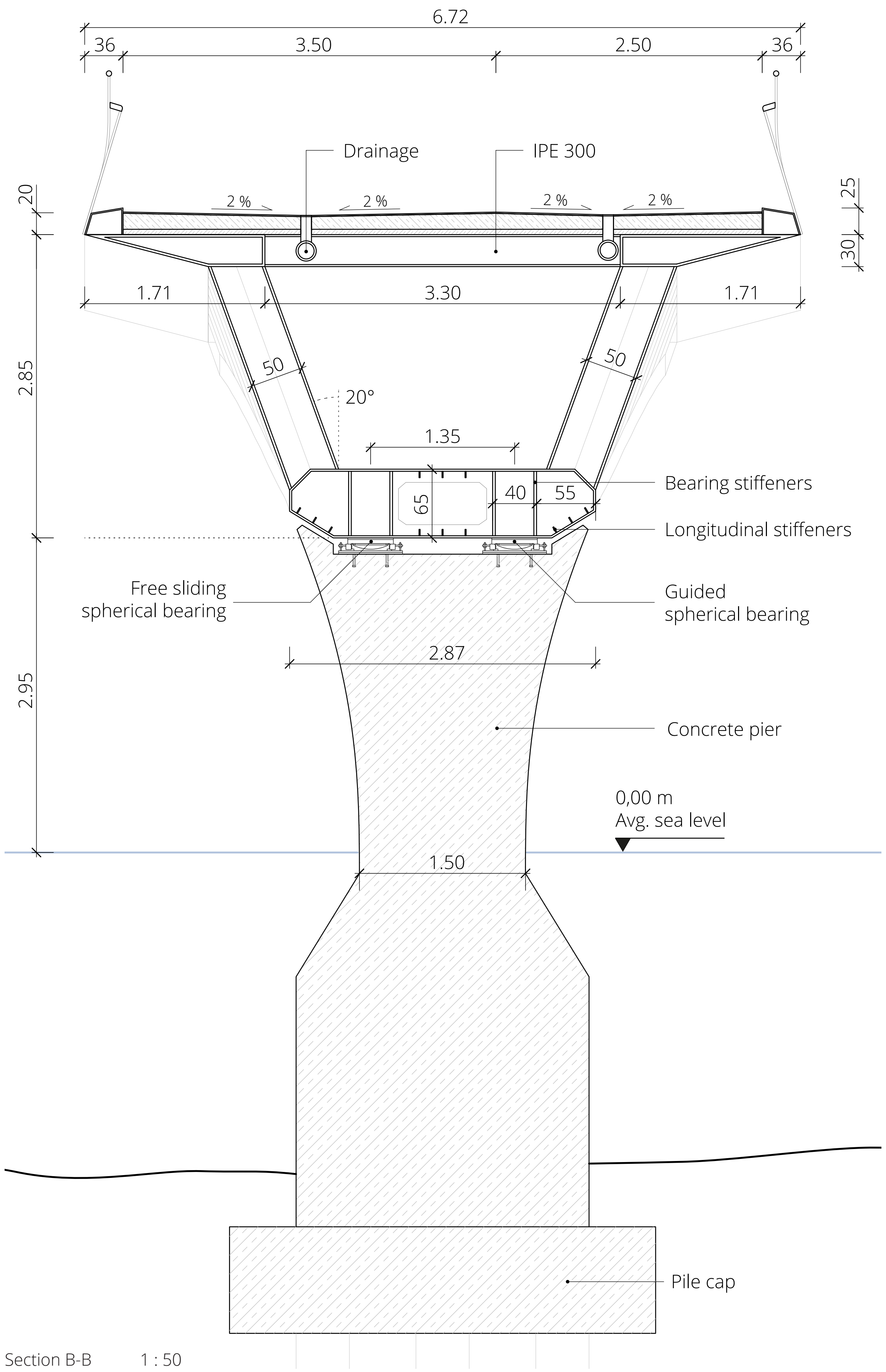
Plan view 1 : 750



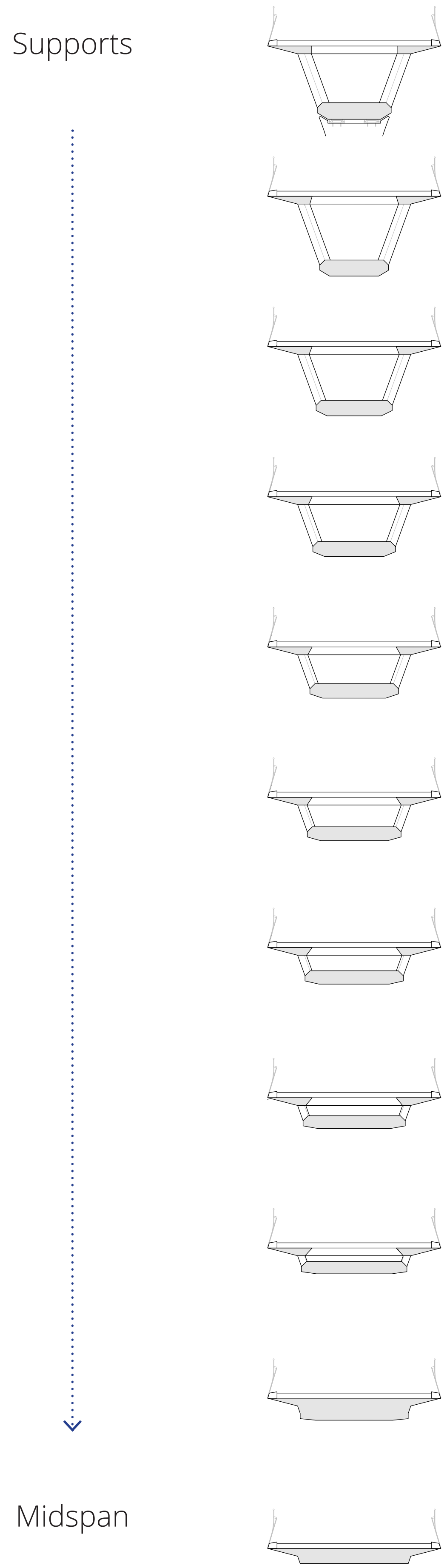
South Elevation 1 : 600



Section A-A 1 : 600



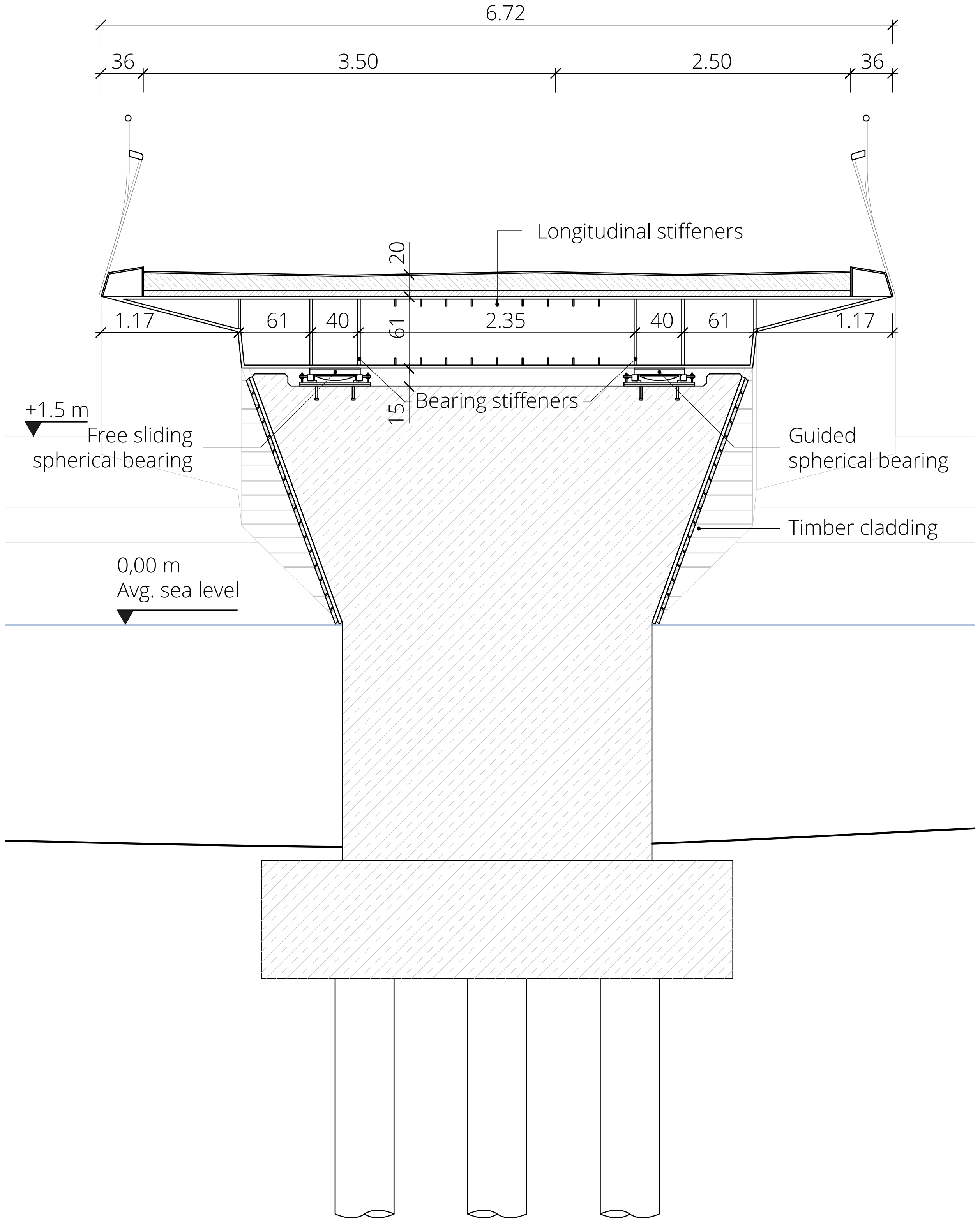
Section B-B 1 : 50



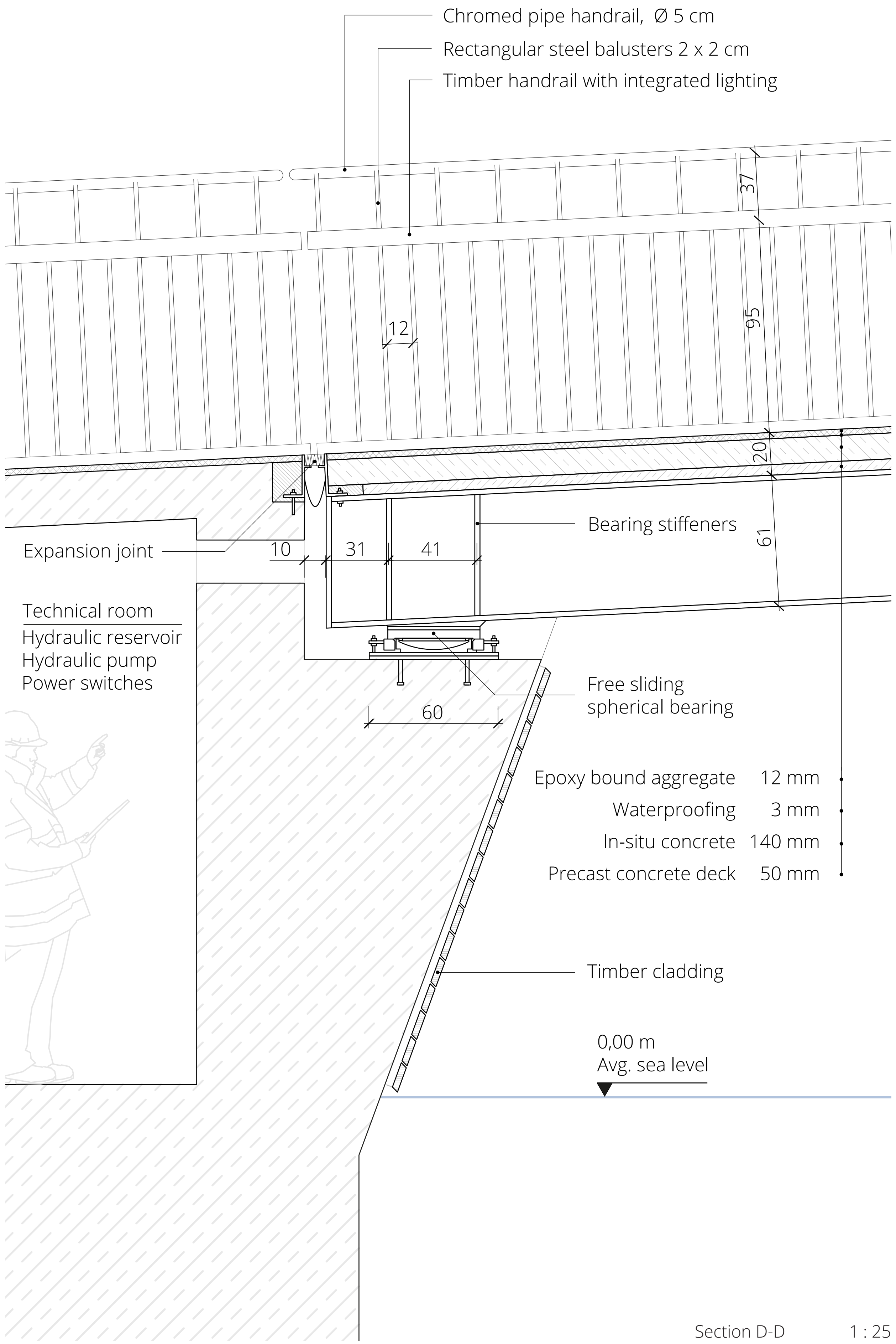
STRUCTURAL CONCEPT

From a structural standpoint, the bridge consists of a sequence of variable depth Vierendeel beams/ trusses with arched bottom chords. The structural layout is composed of a composite deck acting as a top chord (formed by two edge hexagon-shaped box girders linked with transverse beams and a top concrete slab), an octagonal steel box girder acting as a bottom chord, and hexagon-shaped steel box girders contained in vertical planes linking them at a 20° angle. The depth of these vertical elements decreases from 50 cm at the supports to 25cm towards the midspan. The sectional size of these elements and their fixed connections at both ends means they are capable of transferring and resisting bending moments. This makes it possible to have a transparent structure without the need for the triangulated elements contained in a more traditional truss. Although this arrangement is less economical than a traditional truss configuration, it is commonly employed in structures where diagonal elements would interfere with functionality or, as in this case, with aesthetics, creating excessive visual clutter due to the overlap of the inclined planes of structure at both sides of the deck. As the top and bottom chords approach midspan, they merge into a single girder.

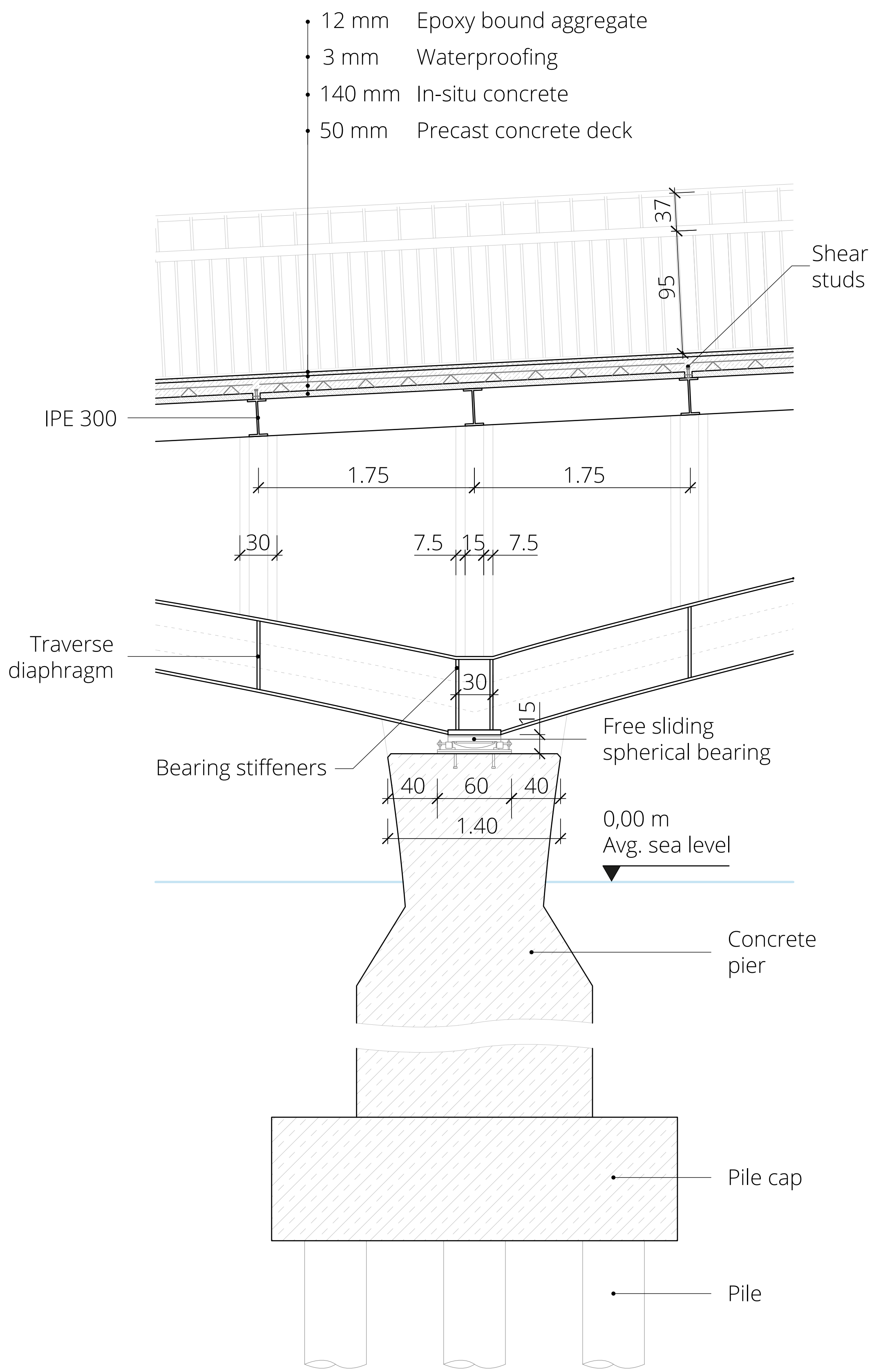
To minimize the expansion and contraction at the opening span, the inner support bearings are of a fixed type that permits rotational movements but prevents translational movements. The outer piers and the abutments each have one guided and one free sliding bearing, which in addition to rotational displacements also enable translational movements. An elastomer expansion joint is used on both ends of the bridge to fill the gap between the bridge and the abutments.

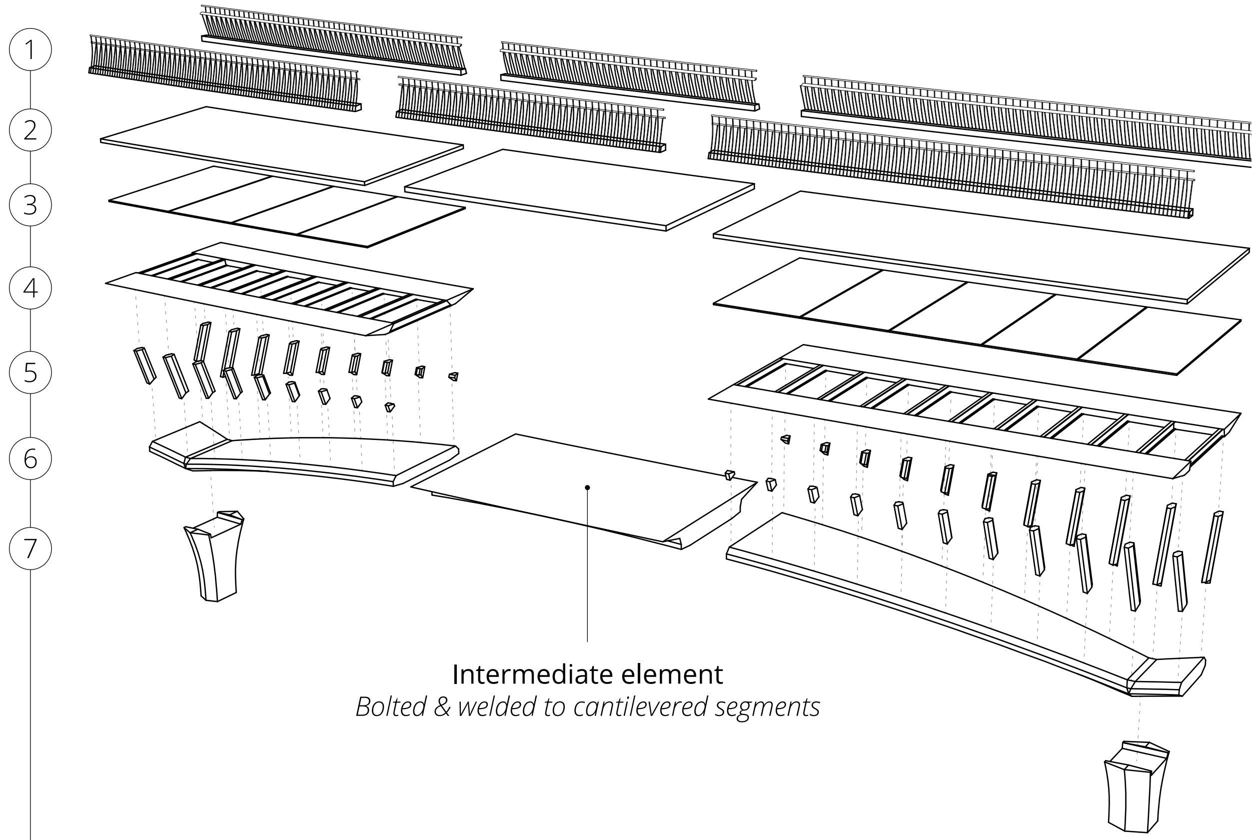


Section C-C 1 : 50



Section D-D 1 : 25

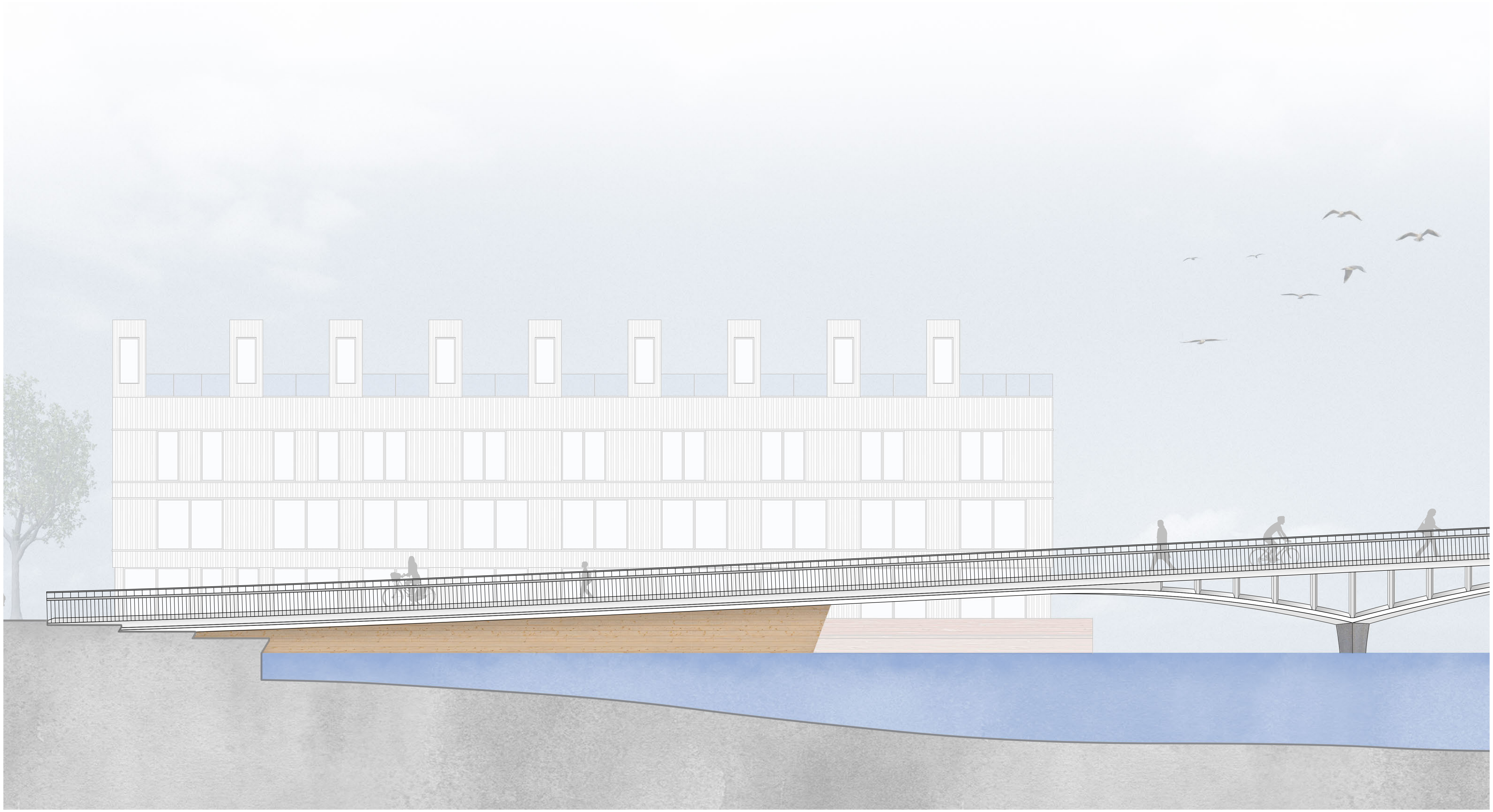




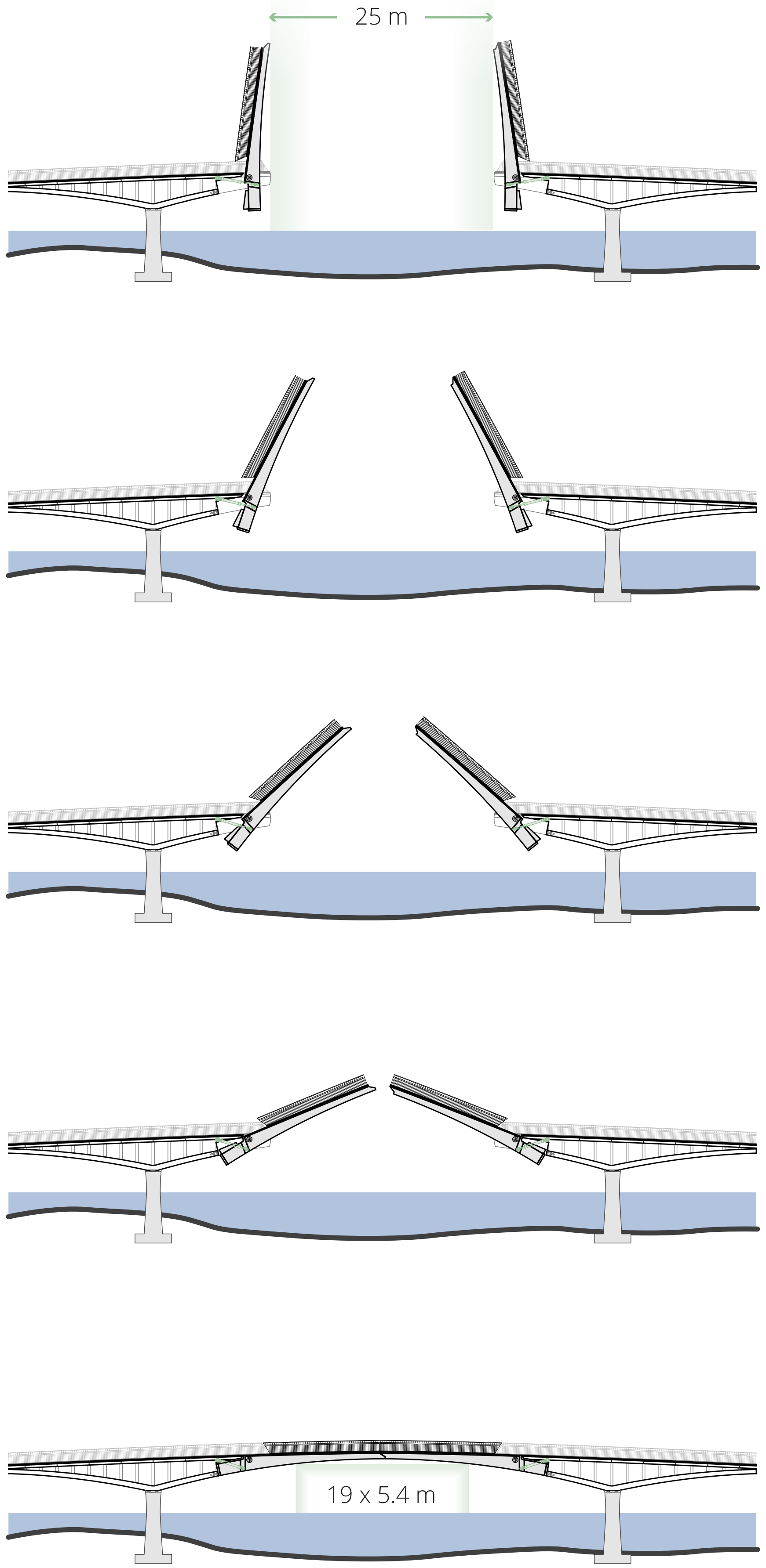
1. Edge beam and parapet
2. In-situ concrete & epoxy bound aggregate surfacing *h= 14 cm + 1,2 cm*
3. Precast concrete deck *h= 5 cm*
4. Top chord trapezoidal girders connected by IPE 300 beams *h= 30 cm*
5. Hexagonal inclined vertical beams *variable height and depth*
6. Bottom chord octagonal girder *variable height and width*
7. Concrete piers

Section E-E 1 : 50

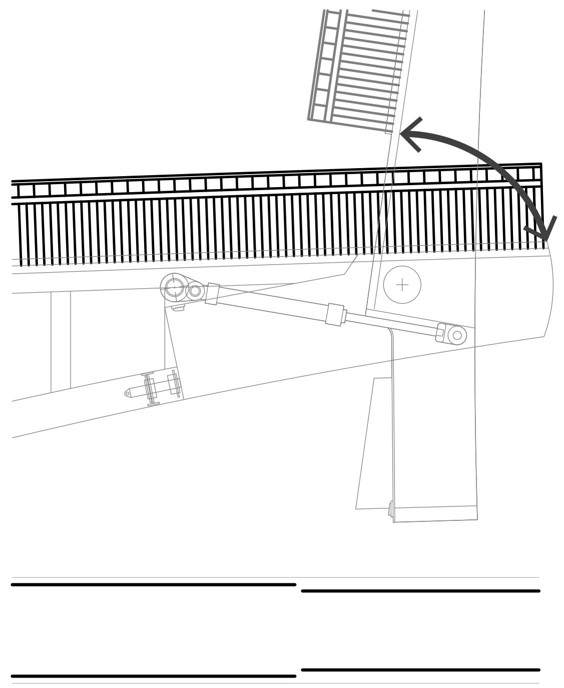
Exploded View



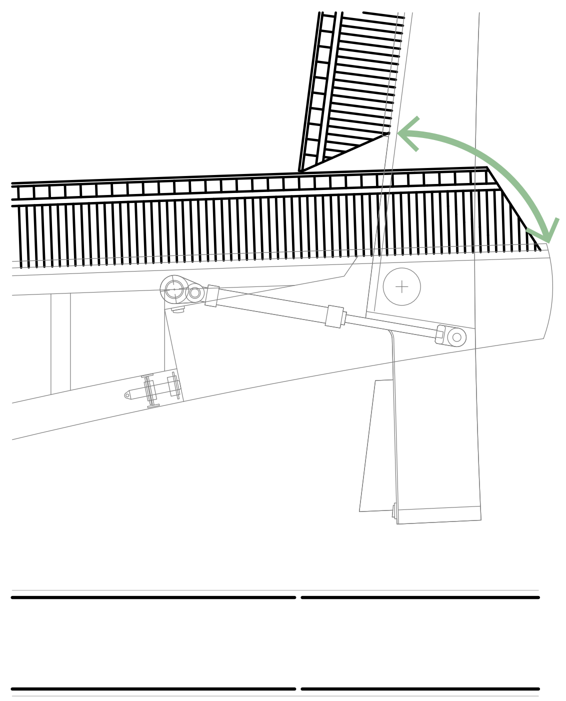
Partial elevation, Teglholmen 1 : 250



Opening sequence



Parapet offset due to clash



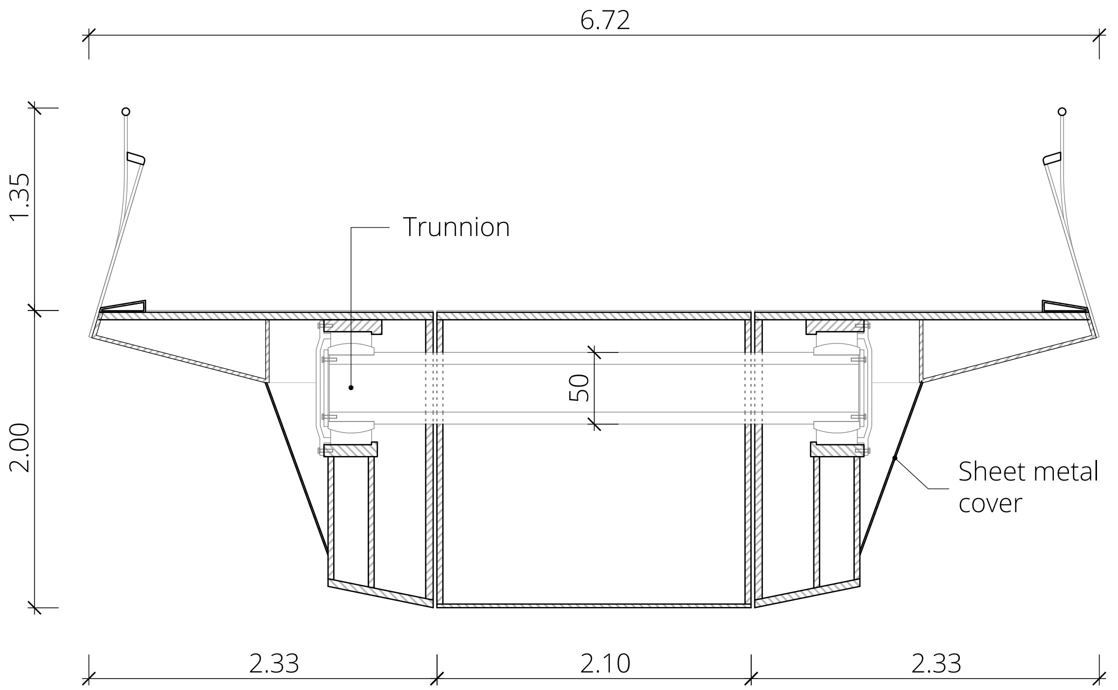
Parapet continuous

BRIDGE OPENING CONCEPT

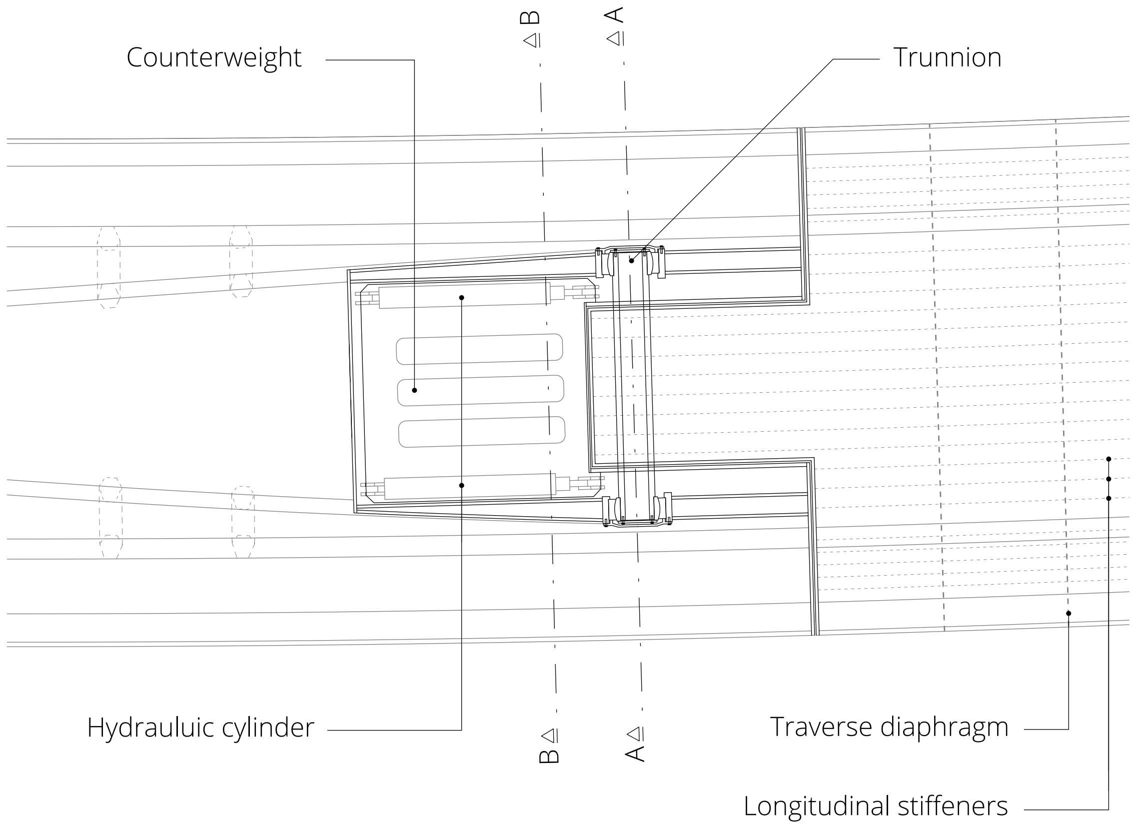
Typologically, the bridge is a double leaf simple trunnion bascule bridge, which is the most common type. However, unlike most bridges in this category, the opening segment does not sit over the supports and is instead cantilevered 10 m from the supporting concrete pier. The bascule mechanism employs two hydraulic cylinders located under the deck surface to push the counterweight down and raise the leaf. The trunnion, cylinders and the counterweight are arranged in such a way that their movement and size is minimised. Each leaf rotates for 80 degrees to give a combined clear passage width of 25 m.

Structurally, the leaf is a single closed steel girder with a thin layer of epoxy bound aggregate on top that acts as a decking surface. The concrete layer is excluded to reduce the dead weight of the leaf. A span lock is utilised in the middle of the complete span, to transfer traverse forces and guarantee identical deflection of the cantilevers in midspan under non-uniform live loads. Additionally, each segment is equipped with a tail lock to help stabilise the leaves under live loads.

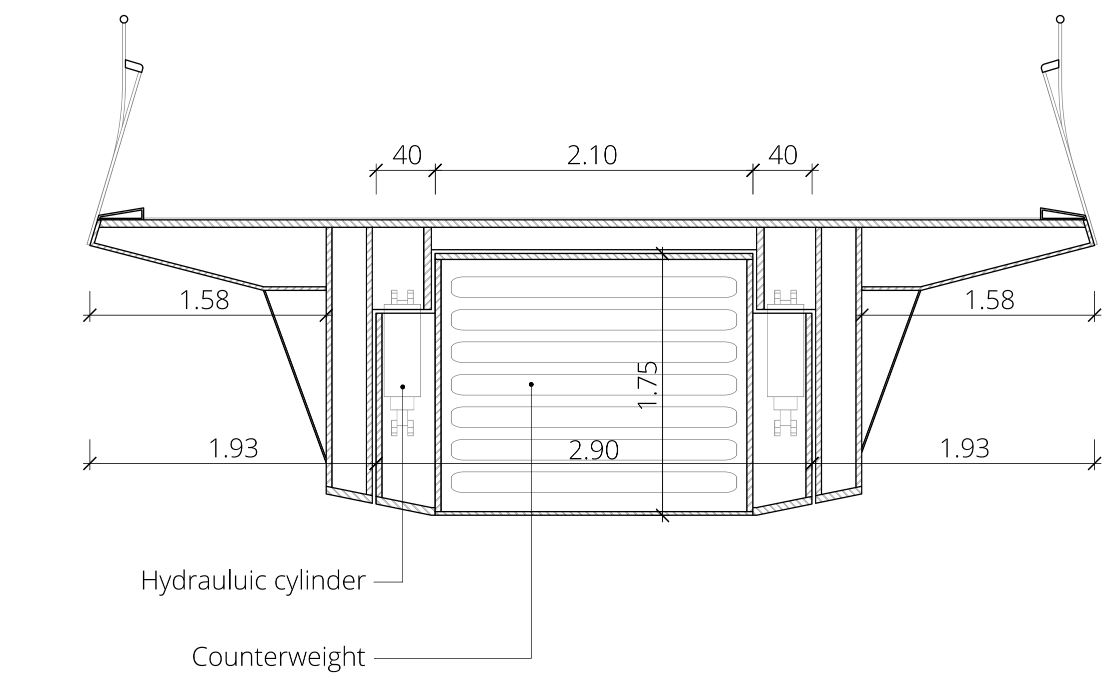
In the closed position, the creases of the steelwork flow continuously throughout the span, with the exception of a few gaps in the main girder between the movable and fixed segments and a 12 cm wide diagonal split of the parapets. The visually cluttered opening mechanism and steelwork holding it together is discretely covered with sheet metal covers between the inclined vertical beams. Ensuring the pivot point and the heel of the bridge are sufficiently spaced allows for the parapet to be split diagonally so that it does not clash with its fixed counterpart during the opening sequence. This provides better visual continuity of the parapet compared to a vertical split where the parapet plane has to be offset to one side.



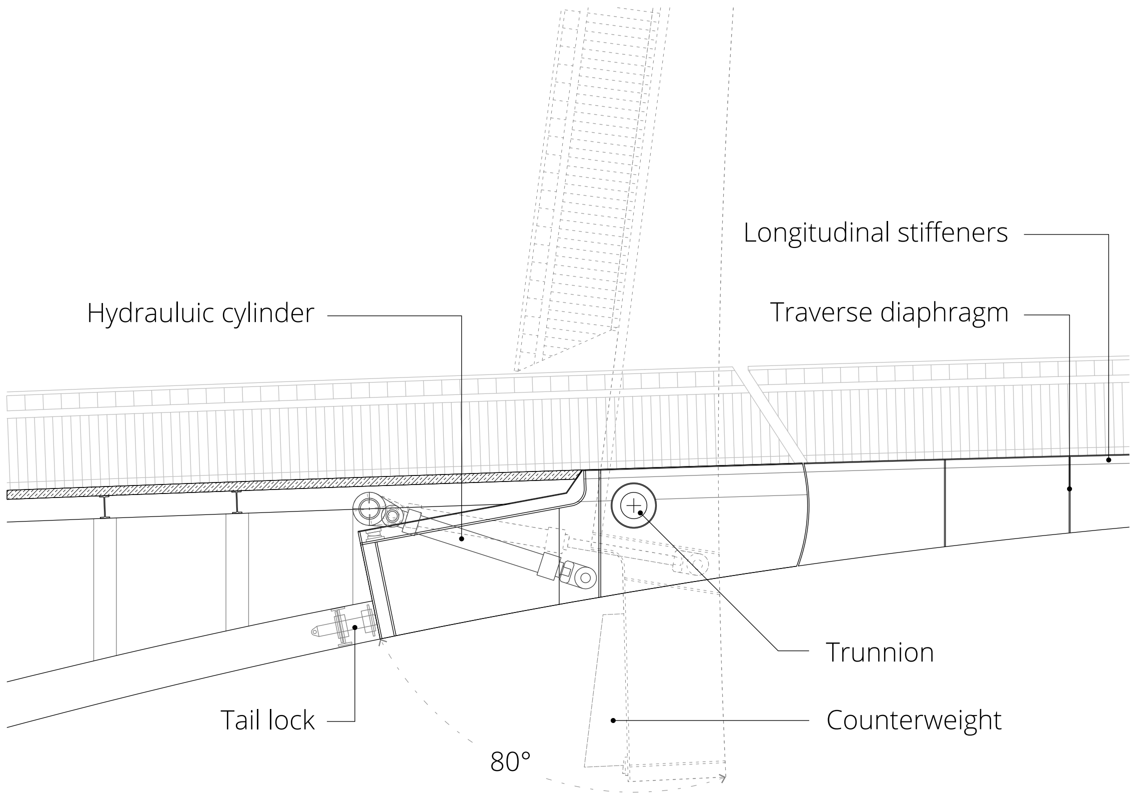
Mechanism section A-A 1:50



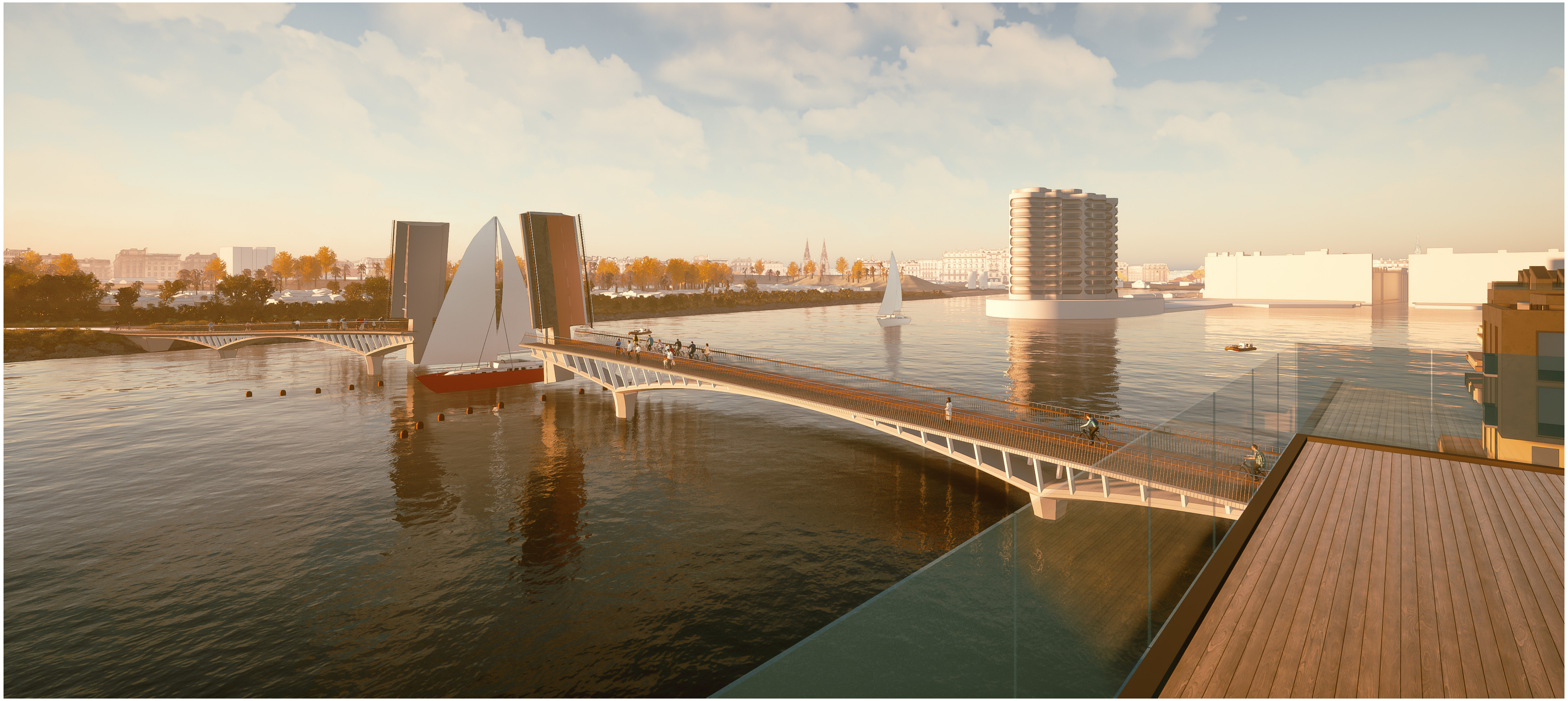
Mechanism plan view 1:100



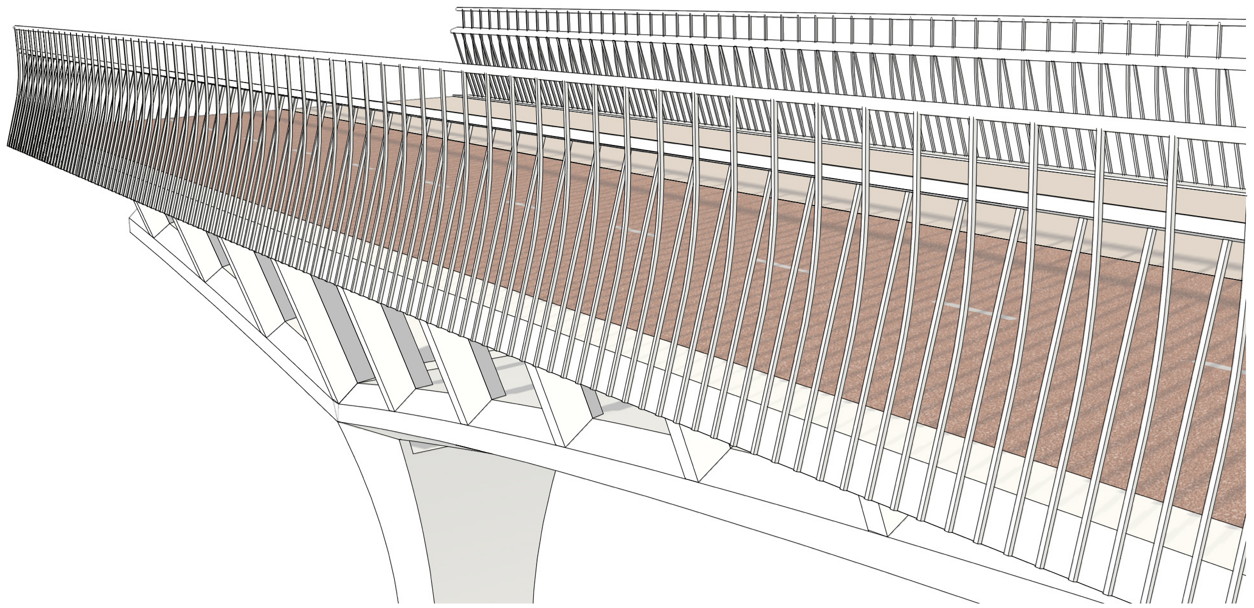
Mechanism section B-B 1:50



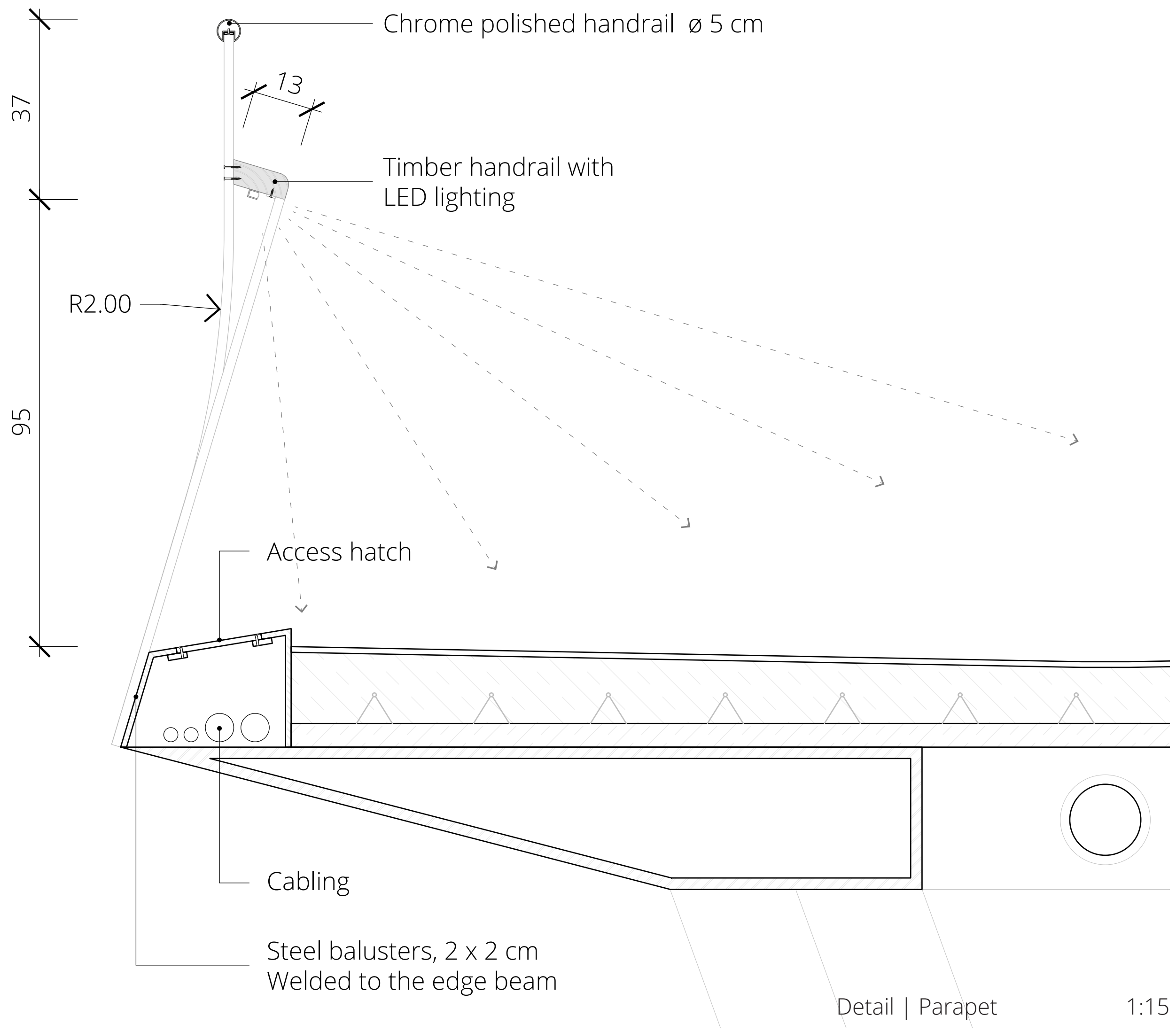
Mechanism long section 1:100



Visualization | View from roof terrace



3D View



Detail | Parapet 1:15

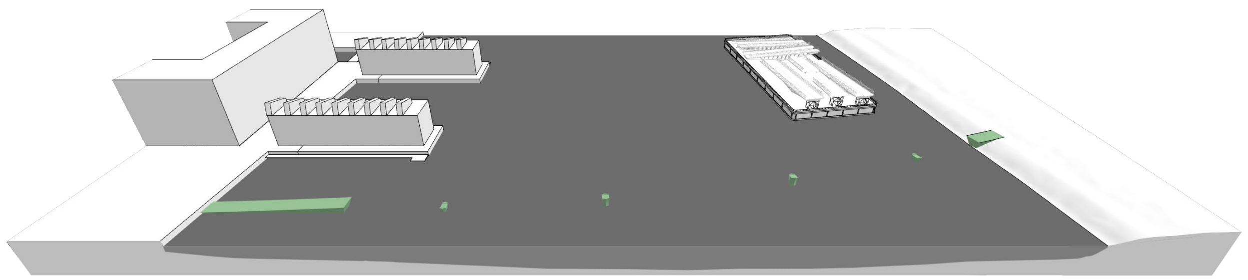
PARAPET

The parapet is composed of an array of rectangular steel bars, which come in two shapes and alternate along the outer face of the edge beam. The shorter 1.2 m straight baluster is inclined by 75 degrees and supports the timber handrail, while the longer 1.5 m baluster bends in the middle so that the top straightens out to a 90-degree angle, with a chrome polished handrail on top. Extending the parapet to the outermost edge gives the deck a more slender appearance.

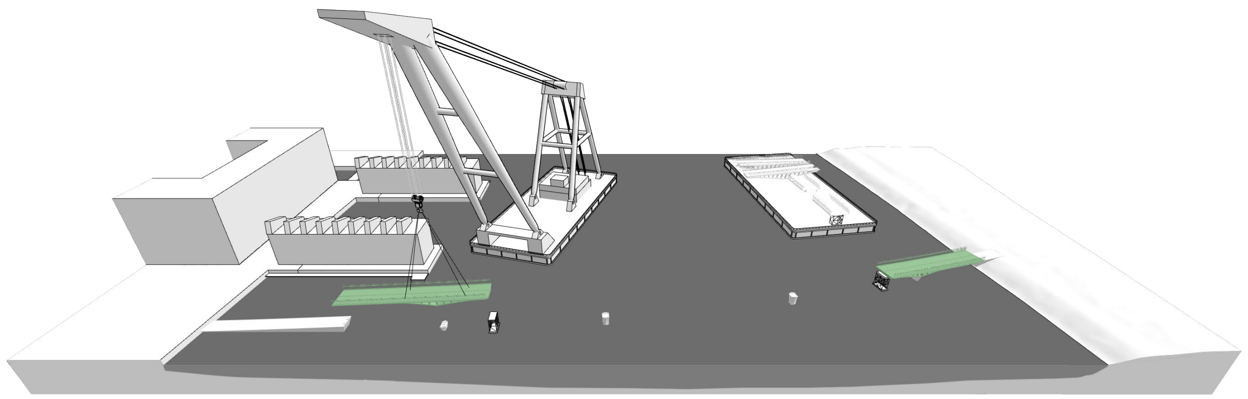
The handrail materials play an important role, in that this element is touched and interacted with more than other elements of the bridge. The lower handrail is made of high-quality mahogany wood and is perpendicularly attached to the short balusters, which makes it inclined by 15 degrees. This results in two main advantages. On the one hand, it encourages users to lean on it and enjoy the views, and on the other hand, it limits the light spill from the LED lamps so that only the deck surface is illuminated. At the same time it also prevents users from being blinded by the direct light. The top chrome-plated rail serves mainly as a guardrail for cyclists. By having a mirror finish, it is less conspicuous and simultaneously expresses superior quality.

Visualization | View from south pier

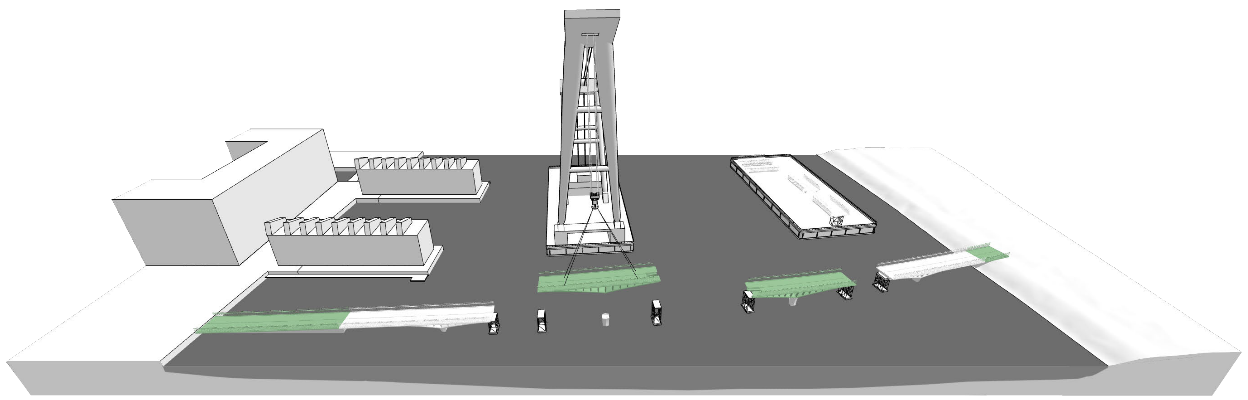
CONSTRUCTION



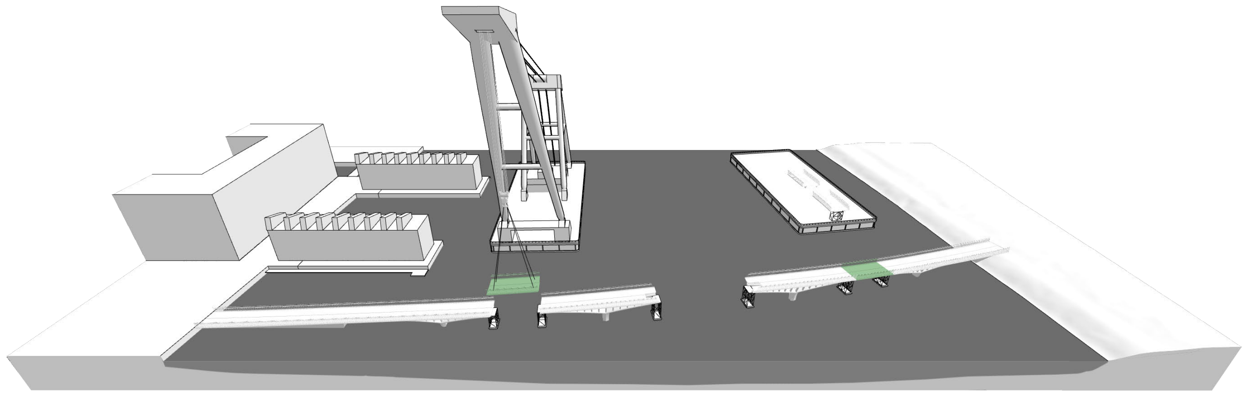
1. Construction of concrete piers and abutments. Pre-fabricated bridge segments arrive on site.



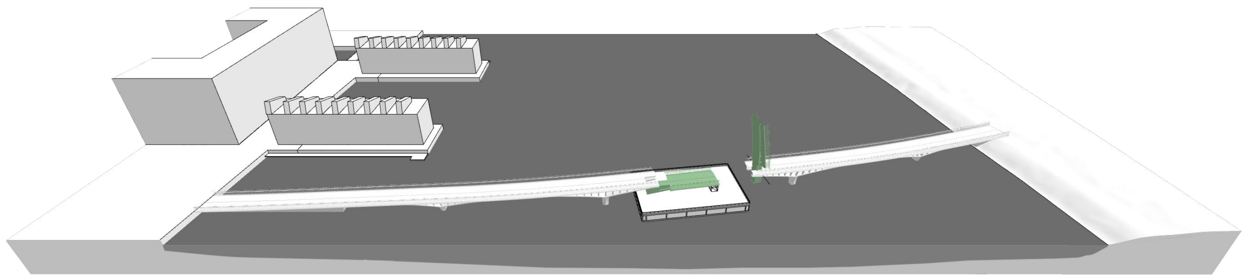
2. Outer segments are lifted into place with a floating crane.



3. Inner segments lifted into place, supported by temporary works on each side.
The abutment decks and parapets are finished from land.



4. Intermediate elements are lifted into place and then bolted and welded with cantilevered segments.

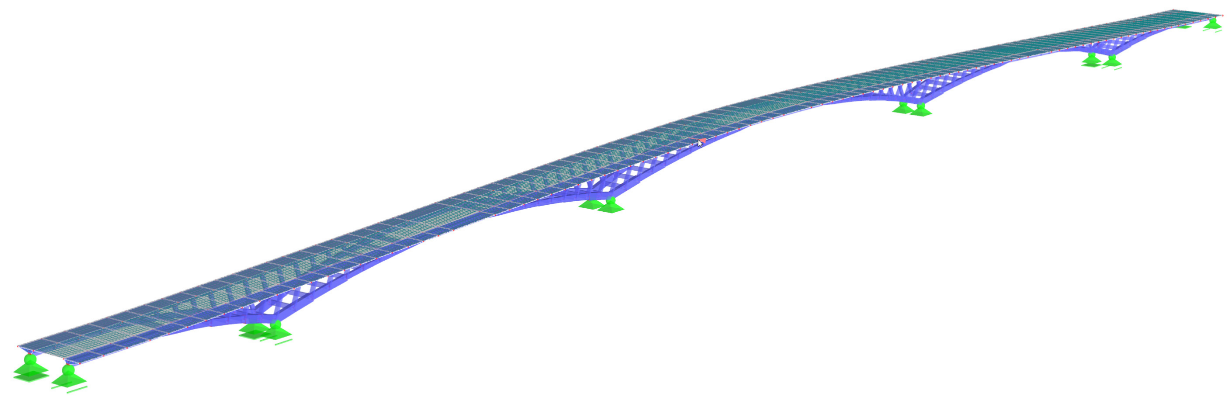


5. Movable segments are installed from below with a raft.

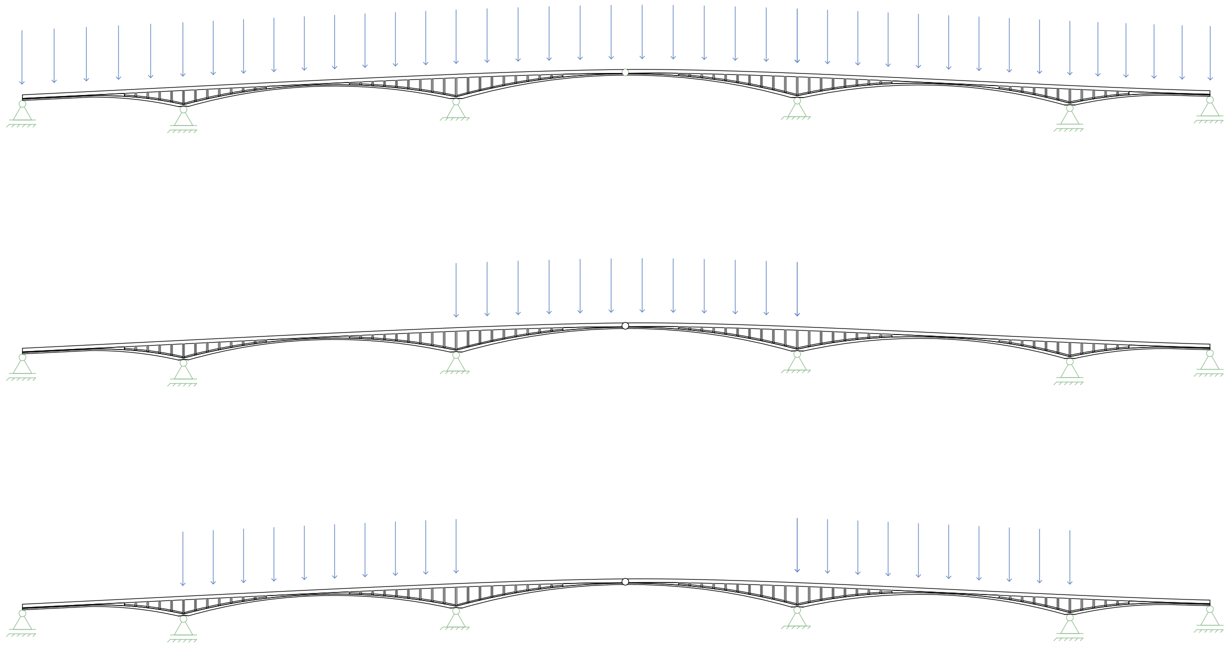
Visualization | Aerial view from south

Visualization | Night view

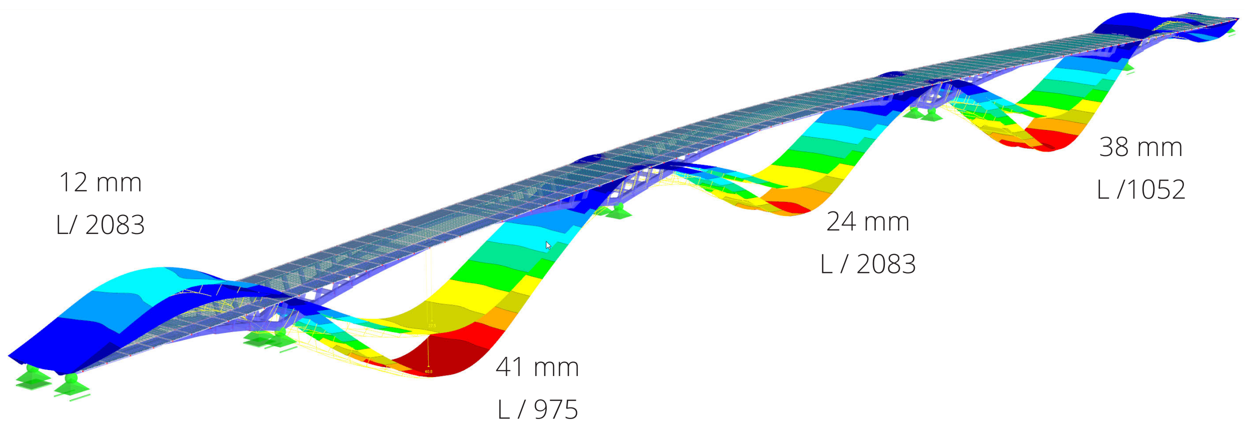
Visualization | Night view



Simplified RFEM model



Load cases | Imposed loads 5kN/m²



Global deformations | SLS Quasi-permanent

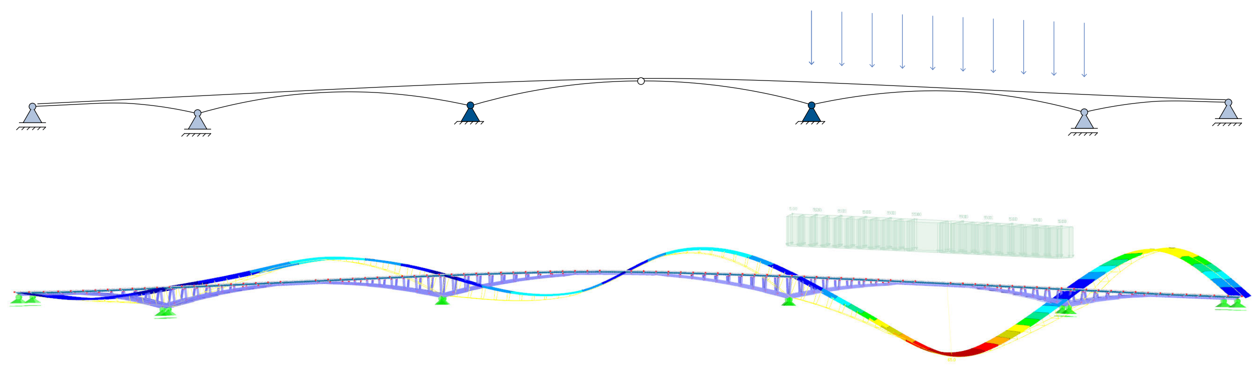
Section No.	Member No.	Location x [m]	S-Point No.	Load-ing	Stress Type	Stress [kN/cm²] Existing	Limit	Stress Ratio
27	TR 350/25/25/300/175/25							
	116	1.070	1	RC12	Sigma Total	-32.87	35.50	0.93
	87	0.000	2	RC12	Tau Total	10.16	20.50	0.50
	116	1.070	1	RC12	Sigma-eqv	33.26	35.50	0.94
28	TO 400/300/25/25/25/25							
	214	0.000	2	RC12	Sigma Total	-25.38	35.50	0.71
	261	0.000	8	RC12	Tau Total	1.71	20.50	0.08
	214	0.000	2	RC12	Sigma-eqv	25.38	35.50	0.72
29	IPN 400 | Arbed							
	338	0.000	1	RC12	Sigma Total	-7.54	35.50	0.21
	338	0.000	13	RC12	Tau Total	-0.17	20.50	0.01
	338	0.000	1	RC12	Sigma-eqv	7.54	35.50	0.21
30	RRO 500x300x20 | ALUKÖNIGSTAHL - EN 10210							
	380	5.000	3	RC12	Sigma Total	15.77	35.50	0.44
	379	0.000	16	RC12	Tau Total	-1.38	20.50	0.07
	380	5.000	3	RC12	Sigma-eqv	15.77	35.50	0.44
31	TO 650/450/25/25/25/25							
	168	0.000	2	RC12	Sigma Total	-21.79	35.50	0.61
	241	0.000	16	RC12	Tau Total	-1.45	20.50	0.07
	168	0.000	2	RC12	Sigma-eqv	21.82	35.50	0.61
32	TO 550/300/25/25/25/25							
	149	0.000	6	RC12	Sigma Total	-22.99	35.50	0.65
	259	0.000	8	RC12	Tau Total	1.36	20.50	0.07
	149	0.000	6	RC12	Sigma-eqv	23.00	35.50	0.65
33	TO 475/300/25/25/25/25							
	212	0.000	2	RC12	Sigma Total	-23.80	34.47	0.69
	173	0.000	8	RC12	Tau Total	1.42	19.90	0.07
	212	0.000	2	RC12	Sigma-eqv	23.80	34.47	0.69

RF-STEEL Members | General stress analysis of steel members | Maximum stresses by cross-section

STRUCTURAL ANALYSIS

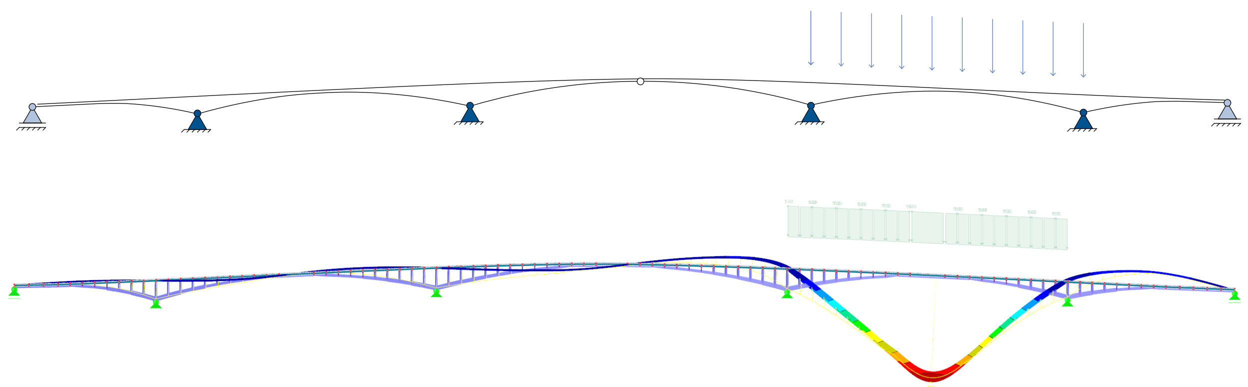
The form-finding process included a preliminary structural analysis, with the main goal of optimizing the ratio between the structural height, the cross section dimensions and the span length, while staying within acceptable deformation limits and the stress limits of the structural material. For the purposes of this analysis, the complex shape of the top and bottom girders has been simplified by using standard steel cross sections (grade S355), which approximate the shape of the proposed bridge design. Three imposed load cases were defined, with uniformly distributed surface loads of 5kN/m², which represent unfavourable scenarios with the bridge fully loaded over all and individual spans. The self-weight and load combinations with appropriate safety factors were automatically calculated and accounted for by the software.

The results of this analysis show that the bridge deformations in the SLS quasi-permanent combination of actions do not exceed the L/800 limit. Furthermore, the ULS stress analysis of steel members shows that the most stressed member is being 94% utilized in this model. It can be concluded that the general proportions of the bridge geometry are structurally feasible, to the extent that further structural optimizations would not fundamentally change the architectural concept.



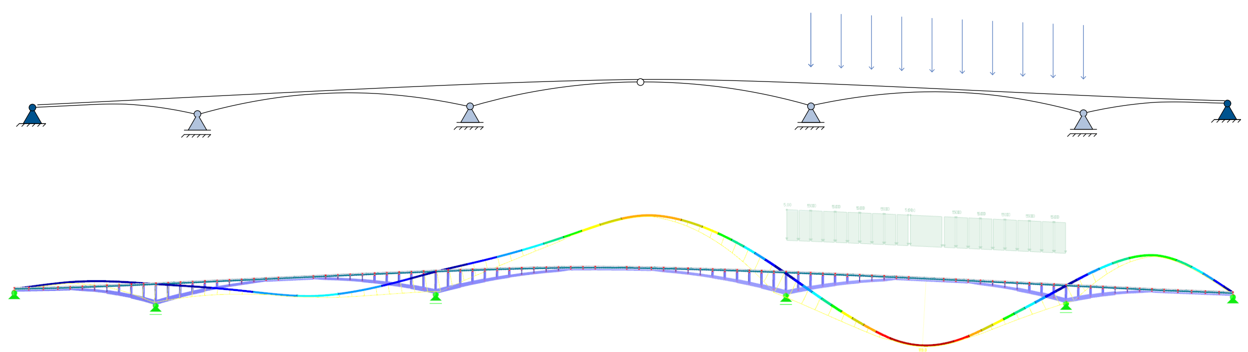
Model A

65 mm



Model B

15 mm



Model C

119 mm

The bridge is structurally a hybrid between an arch and a Vierendeel truss. To determine the extent to which each of these structural aspects are utilised, three structural models with support systems matching their optimal utilisation were compared. The actual model (Model A) has supports fixed on the inner piers, allowing only rotational deformations, while the outer piers and abutments have free sliding bearings. For the arch utilisation model (Model B), all the bearings except for the abutments were set to a fixed type, resulting in horizontal loads from the arch being transferred to the concrete piers. The Vierendeel truss model (Model C) does the reverse, with the abutment bearings fixed and the rest of the bridge allowed to slide longitudinally. The maximum deformations of each model under a uniformly distributed load were then compared using the formula:

((Model A - Model C) / (Model C - Model C)) x 100

This indicated that up to approximately 52% of the structure will be utilised as an Arch and 48% as a Vierendeel truss.

CONCLUSION

Cycling is the staple of culture in Copenhagen, which has been ranked the world's top cycling city multiple times. By prioritizing the cycling infrastructure over many decades, the bicycle has become the preferred method of transportation. In recent years numerous bridging schemes have been developed in order to further improve the cycling network. The popularity of these bridges - backed by the rapidly increasing number of daily users - shows that there are still missing connections waiting to be linked.

The proposed footbridge offers an attractive and enjoyable crossing for pedestrians and cyclists across the harbour of Copenhagen. Design decisions have been made by carefully taking into account multiple aspects - such as navigability, the crossing experience and viewing angles - without compromising the importance of one aspect over the other. The gently curved alignment seamlessly integrates with the existing cycling network and simultaneously makes the structure visually more dynamic and interesting. The bridge reflects the modern character of the newly-built residential district without disturbing the delicate environment of the opposing side and forms new connections to the capital's biggest natural attraction.

BIBLIOGRAPHY

Baus, Ursula/Schlaich, Mike: Footbridges. Construction, Design, History, Basel 2008

Bendiks, Stefan/Degros, Aglaée: Cycle Infrastructure. Rotterdam 2013

Berg, Christa van Den: Brief Dutch Design Manual for Bicycle and Pedestrian Bridges. Delft 2015

Calgaro, Jean-Armand/Tschumi, Marcel/Gulvanessian, H., Designer's Guide to Eurocode 1: Actions on Bridges : EN 1991-2, EN 1991-1-1, -1-3 to -1-7 and EN 1990 Annex A2, London 2010

Colville-Andersen, Mikael: Copenhagenize. The Definitive Guide to Global Bicycle Urbanism, Washington DC 2018

Dupre, Judith: Bridges. A history of the world's most spectacular spans, New York City 2007

Fédération Internationale Du Béton, Guidelines for the Design of Footbridges: Guide to Good Practice, in: Bulletin 32, 1-154

Keil, Andreas: Pedestrian Bridges. Ramps, walkways, structures, Munich 2013

Koglin, Terry L.: Movable bridge engineering. Haboken 2003

WEBLIOGRAPHY

Central Scotland Green Network: CSGN Green Cycle Routes,
Online under: http://www.centralscotlandgreennetwork.org/campaigns/green-active-travel/green-active-travel-2 [29.12.2020]

City Population: Copenhagen,
Online under: https://www.citypopulation.de/en/denmark/copenhagen/K04__vesterbro_kongens_enghave/ [5.6.2020]

Dansk Arkitektur Center: Teglholmen,
Online under: https://dac.dk/viden/arkitektur/teglholmen/ [5.6.2020]

Knight, Martin (8.9.2017): BIM and the Art of Motorcycle Maintenance,
Online under: https://structurae.net/en/literature/conference-paper/bim-and-the-art-of-motorcycle-maintenance?downloadFullPdf=1 [2.6.2020]

Københavns Kommune (2012): Good, Better, Best, The City of Copenhagen's Bicycle Strategy 2011-2025,
Online under: https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=823 [29.12.2020]

Københavns Kommune (2015): Copenhagen Green Accounts 2014,
Online under: https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1393 [29.12.2020]

Københavns Kommune (2015): Municipal Plan 2015,
Online under: https://kp15.kk.dk/artikel/municipal-plan-2015 [29.12.2020]

Københavns Kommune (2019): The Bicycle Account 2018,
Online under: https://kk.sites.itera.dk/apps/kk_pub2/pdf/1962_fe6a68275526.pdf [2.1.2021]

Københavns Kommune (2020): Local plan 310,
Online under: https://blivhoert.kk.dk/hoering/teglvaerkshavnen-tillaeg-11-lokalplan-310-11 [29.12.2020]

Larsen, Marie K. (2010): Analysis of the Danish Travel Survey data on private and public transportation,
Online under: https://www.trafikdage.dk/papers_2010/406_MarieKLarsen.pdf [29.12.2020]

Movia (28.6.2018): Copenhagen's New Harbour Buses,
Online under: https://www.kk.dk/sites/default/files/uploaded-files/movia_-_presse_og_nyheder.pdf [29.12.2020]

Orskov, Stig (21.6.2000): Udstødningshavnen,
Online under: https://www.information.dk/2000/06/udstoedningshavnen [8.6.2020]

Paulsen, Mads (2019): Large-Scale Assignment of Congested Bicycle Traffic Using Speed Heterogeneous Agents,
Online under: https://www.researchgate.net/publication/333258472_Large-Scale_Assignment_of_Congested_Bicycle_Traffic_Using_Speed_Heterogeneous_Agents [21.5.2020]

Pendlebury, John (2.6.2017): Heritage, urban regeneration and place-making,
Online under: https://www.tandfonline.com/doi/full/10.1080/13574809.2017.1326712 [29.12.2020]

Soeters, Sjoerd: Sydhavnen/Sluseholmen Copenhagen Harbour renovation project 2000-2009,
Online under: https://pphp.nl/wp-content/uploads/2017/05/SLUSEHOLMEN.pdf [29.12.2020]

Teknik- og Miljøforvaltningen (2014): Administrative basis for bridge opening in the Port of Copenhagen,
Online under: http://kk.sites.itera.dk/apps/kk_pub2/pdf/1280_yFF4l4mvFl.pdf [29.12.2020]

Teknik- og Miljøforvaltningen (2016): Requirements and guidelines for bridges and other structures in the City of Copenhagen,
Online under: https://kk.sites.itera.dk/apps/kk_pub2/index.asp?mode=detalje&id=1461 [29.12.2020]

US Modernist Radio (2.6.2020): Podcast #146/Bridges as Architecture: Europe's Martin Knight,
Online under: https://podcasts.apple.com/us/podcast/146-bridges-as-architecture-europes-martin-knight/id986108444?i=1000476398581 [2.1.2021]

Visit Copenhagen: Lille Langebro,
Online under: https://www.visitcopenhagen.com/copenhagen/planning/lille-langebro-gdk1111450 [21.5.2020]

Walker, Peter (26.11.2015): Copenhagen glass-walled bicycle bridge plans abandoned,
Online under: https://www.theguardian.com/world/2015/nov/26/copenhagen-gate-glass-bicycle-bridge-abandoned-steven-holl [2.6.2020]

LIST OF FIGURES

Interactive map of Copenhagen including 2D maps and aerial photos,
Online under: http://kbhkort.kk.dk/

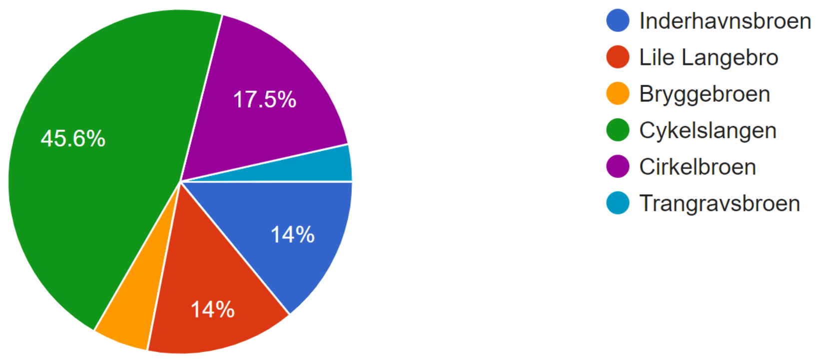
3D model of the City of Copenhagen
Online under: https://www.opendata.dk/city-of-copenhagen/bymodel-3d-kobenhavn

APPENDIX

1. Survey directed at the residents or regular commuters to Copenhagen.

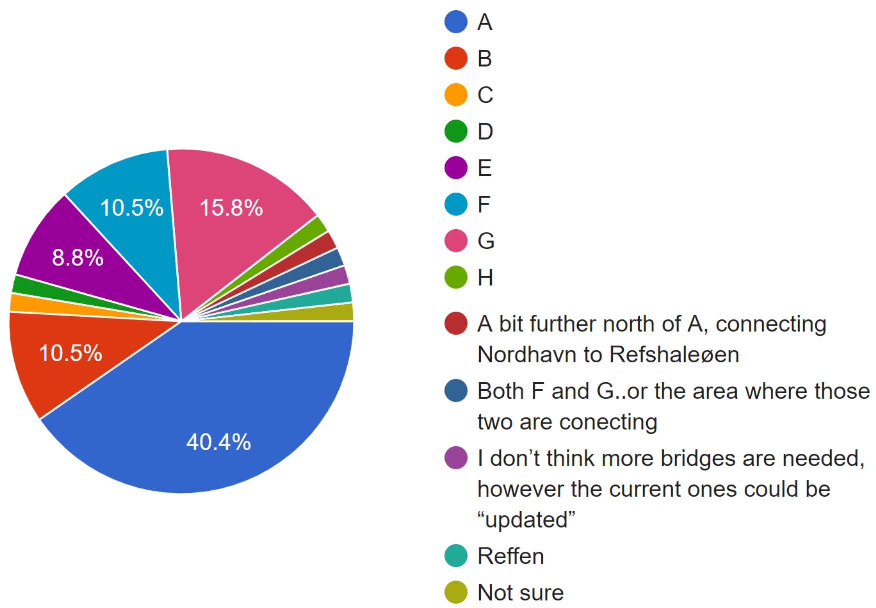
Which of the following bridges do you enjoy the most?

57 responses



Where do you see the biggest potential for a new bicycle/pedestrian bridge?

57 responses



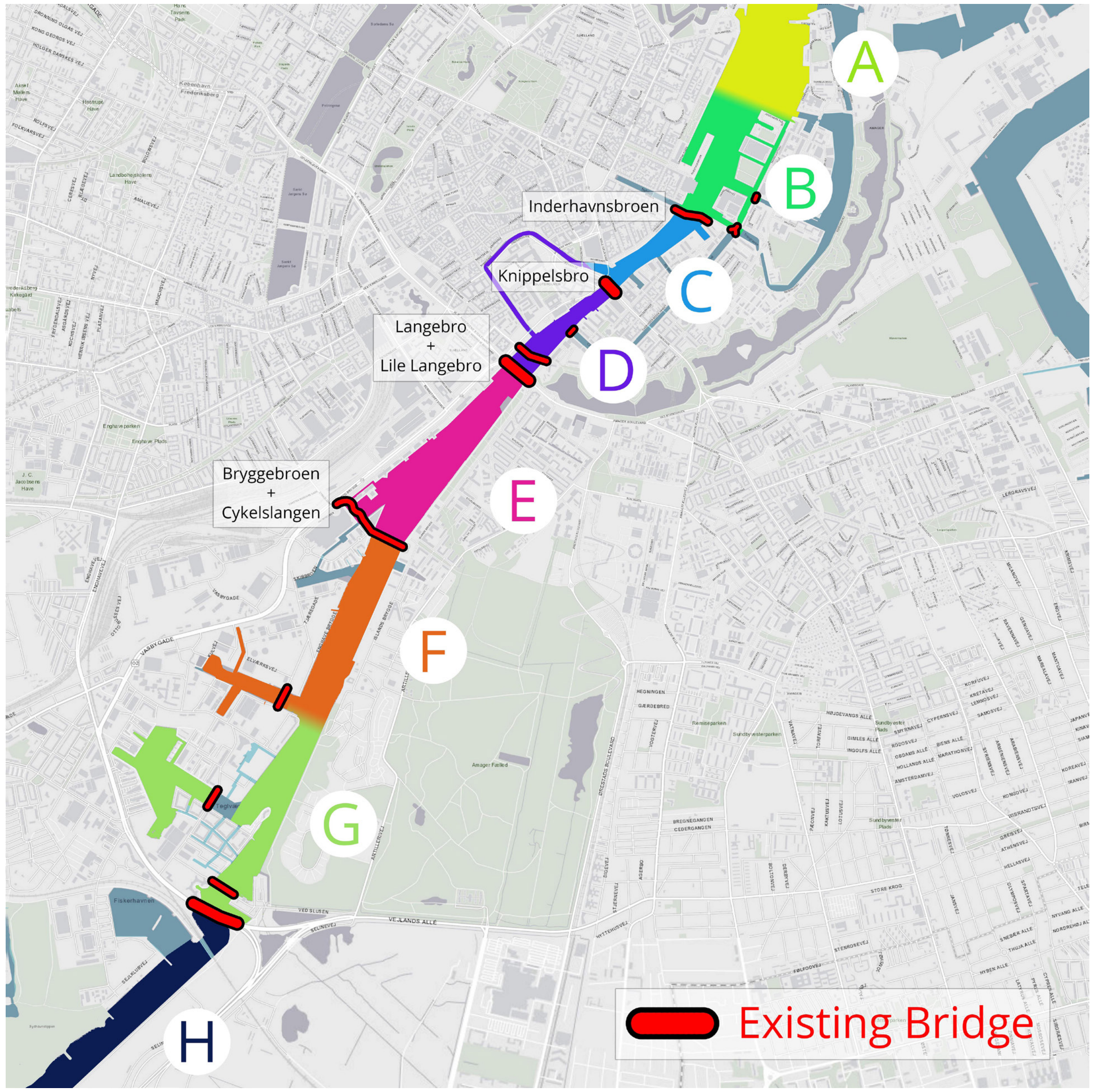
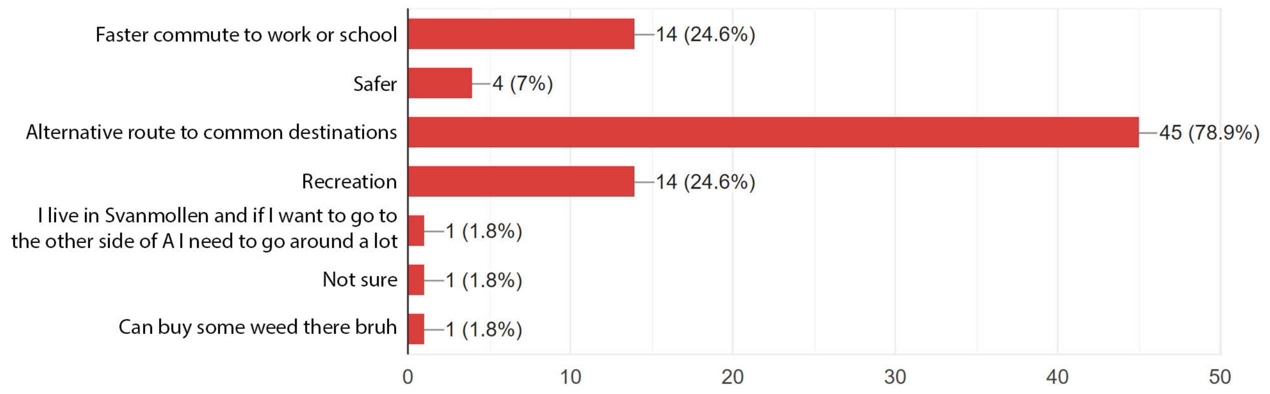


Image to the question: Where do you see the biggest potential for a new bicycle/pedestrian bridge?

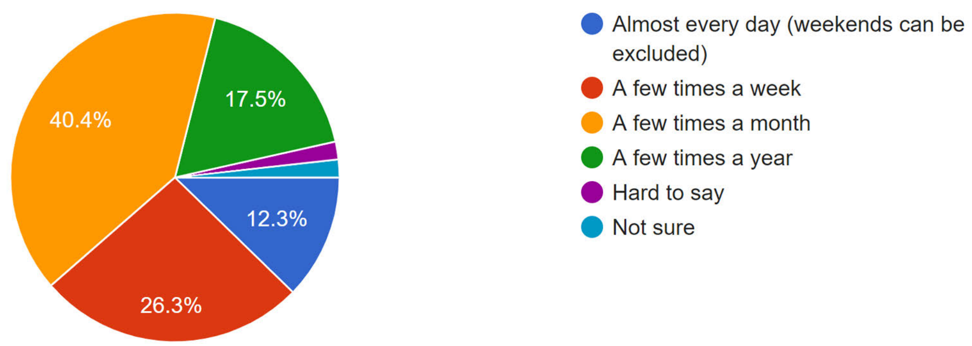
How would this bridge benefit you personally?

57 responses



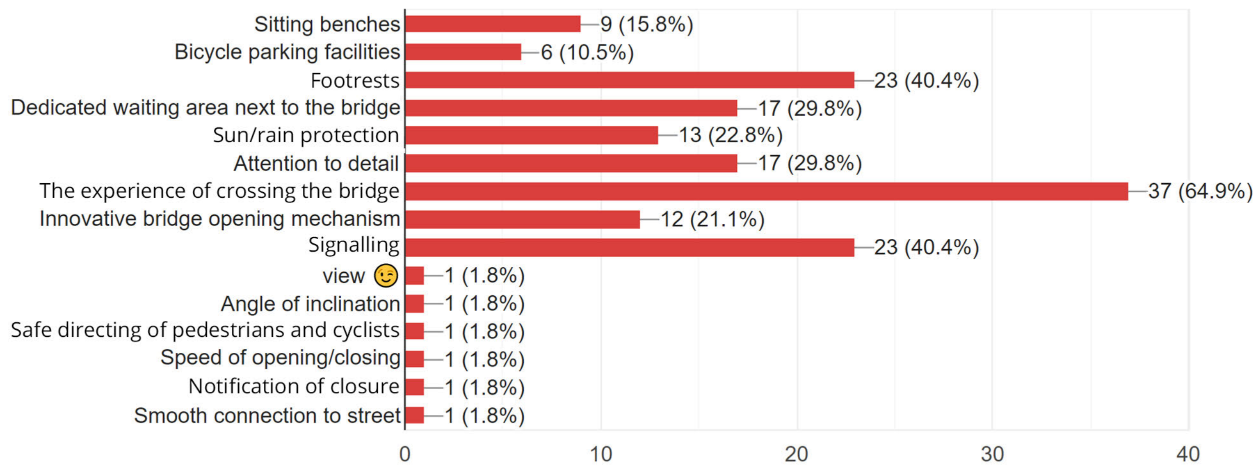
If built, how often would you use this bridge?

57 responses



Which features and aspects of a movable (opening) bridge are important to you?

57 responses



Do you have any specific notes on what should be implemented in a good bicycle/pedestrian bridge design or something that should be avoided?

1. Turning lanes
2. I think that the biking lanes should be made in a material that ensures safety e.g. when it is raining. I am very thankful for Bryggebroen, but it really doesn't feel safe in rain. This is also because it is very narrow and its rails are a bit too low, in my opinion.
3. Maybe a sign stating clearly what are you supposed to do when you're crossing the bridge and the lights start to go on.
4. Keep in mind how bicycles are moving. 90degree angles just don't work (inner city bridge vs. cykelslange).
5. Very distinct separation between cyclists and pedestrians. (important). Safe turns on the bicycle paths.
6. More space for pedestrians (Wider).
7. The entrance and exit to the bridge - the right angle from the cycle lane, clear separation of bike and footpath. Angle of inclination - Inderhavnsbroen is too steep. Smoothness (again, Inderhavnsbroen has a sharp bend in the middle, which in combination with the inclination isn't too pleasant to cycle.
8. Crossing pedestrian and bicycle traffic at the beginning and end.
9. Take the local design philosophy into account. Simplicity and functionality. Look at the bridges (also other places) by Dissing & Weitling. Enjoy your work :)
10. Crossing for pedestrians & cyclists and cars are a bit confusing with some bridges, for example with Lille Langebro on the side of Christianshavn. Its a bit unsafe, especially during rush hours to cross/join the main road after crossing bridge. There can be load of traffic. Maybe more space or signage on the floor could help.
11. Make sure the cycle lane is separated from the pedestrian one.
12. The biggest problem with bridges in Copenhagen is that they are really going uphill, and have terrible division between pedestrians and bikes.

13. Good design, fun to ride but most importantly - it should make sense. Entrance and exit from bridge should do too! Bryggebroen for examples has a quite bad entrance/exit situation.

14. Adequate infrastructure entering/exiting bridges.

15. No sudden turns at the bottom/end.

16. Do not block passage of boats.

17. Clear pedestrian (bike) line, so you don't jump over pedestrians being confused where they need to walk. The areas where there are many tourists are especially prone to this problem.

18. I will enjoy more if there are more invited space on the bridge, some benches or spaces for staying.

19. Dedicated viewing area (for taking pictures)