Engineering the Lille Langebro

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The Lille Langebro at night, Image: Peter Nugent

Where the project took place

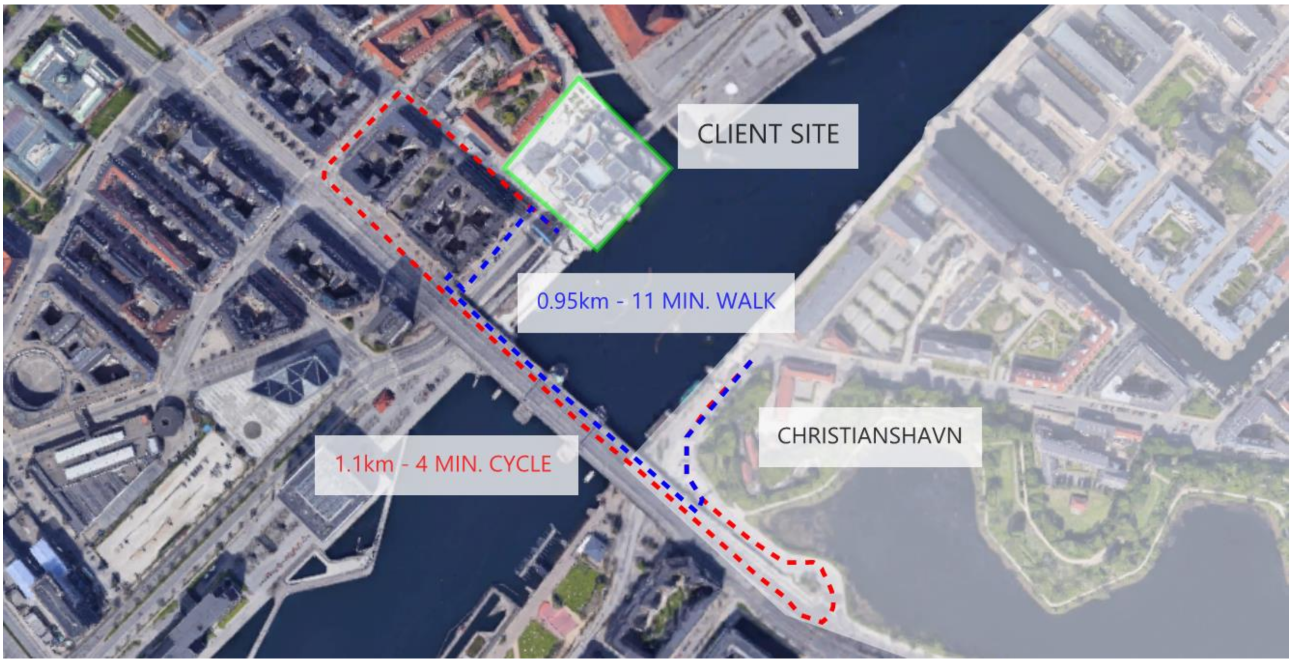
The city of Copenhagen has a rich history of impressive bridges and construction in this decade has followed this tradition. The Cirkelbroen, Cykelslagen and Inderhavnsbroen are three examples of imaginative bridges recently constructed. Connectivity for cyclists and pedestrians as well as development of the harbour area is a key priority for the city as evidenced by these bridges, amongst other projects. In late 2016 it became the first city to have more cyclists than cars, demonstrating the need for safer and dedicated cycle routes[1].

The Cirkelbroen (Circle Bridge) (© User:Colin / Wikimedia Commons / CC BY-SA 4.0), Cykelslagen (Cycle Snake) (Image: Peter Nugent) and The Inderhavnsbroenare (Inner Harbour Bridge) (© User:Colin / Wikimedia Commons / CC BY-SA 4.0)

Why the bridge was needed

The proposed site for the Lille Langebro Bridge had poor connectivity between Christianshavn and the centre of the city. Cyclists and pedestrians were forced to use the Langebro Bridge cycle lane which is rather narrow and not easily accessible by wheelchair. The client owned a small plot of land to the Northwest of the Langebro and commissioned a bridge project – with the aim of improving connectivity to their development and across the harbour - which was gifted to the municipality of Copenhagen. The challenge was to design an iconic footbridge that seamlessly integrated with the site and allowed ships to continue through the harbour.



Map of the journey time prior to the Lille Langebro construction

The superstructure

The resulting design was a slender form that graciously curves across the harbour. The superstructure is formed from two triangular steel box sections running the length of the bridge. The section is non-uniform and twisted along its length, creating the effect of a wing lifting up towards mid-span and descending at the abutments. The result is doubly curved plates that give the bridge a clear line where light meets shade. The plan alignment sweeps across the harbour to join the existing roads on either side. Cross members are spaced every three metres beneath a 7.5m wide x 12mm steel deck plate lined with longitudinal stiffeners to form an orthotropic deck. The span is 160m split into four spans with two fixed piers and two moveable piers. The bridge swings open to allow ship passage which is a contrast to the Langebro Bridge which is a bascule bridge. Typically, moveable bridges have a pin connection at mid-span which results in deeper sections over the supports. The Lille Langebro has a moment resisting connection at mid-span resulting in more slender sections over the supports.

How to represent the complex bridge for analysis

The bridge geometry was defined by the architect in Rhinoceros and an analysis model was created at the scheme design and detailed design stages in MidasCivil. A line model was employed during scheme design because it provided a quick and agile solution to represent the geometry that was likely to be subject to change. A more sophisticated model was required to fully understand the global stress distribution across the bridge, specifically under a nonlinear analysis. The deflections, particularly under thermal loading, needed to be investigated further with the bridge's geometry represented at a greater resolution as they were critical to the design of the connections.

The Lille Langebro during the day looking across the harbour, Image: Peter Nugent

A shell model was created by interrogating the architect's model to approximate the geometry of the curved plates using a series of dummy line elements and nodes. Shell elements were created automatically by numbering the nodes in a predictive manner and utilising the Midas Civil Text (MCT) Command Shell. This centralised model was used to create nonlinear, dynamic and localised models. The model creation provided an efficient way to generate an accurate representation of the bridge longitudinal girders, whilst the secondary elements were represented as lines beam elements. Preparing this model highlighted the need for better workflows and improving the way models are created, specifically for structures that cannot be generalised or simplified.

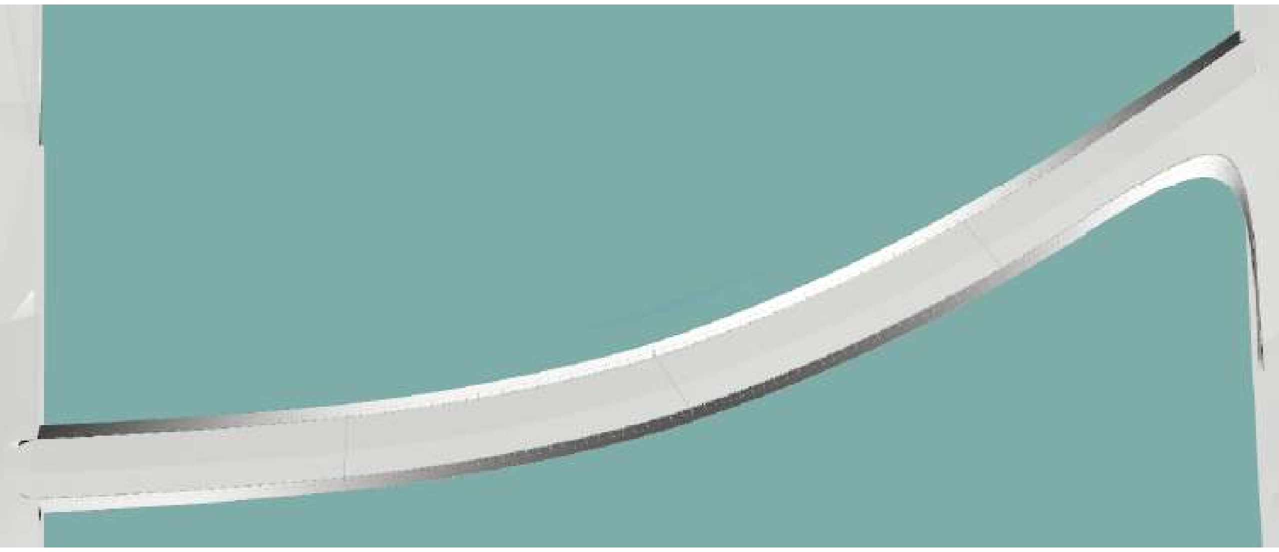
Understanding the effects of temperature

The alignment of the joints is critical for the bridge to function. A key driver in the movement of bridges is the effect of temperature which causes the bridge to expand under high temperatures and contract under low temperatures. Temperature differences between the different faces of the members can also cause rotation and displacement. The global effect of temperature is easily applied in the majority of analysis packages, whereas the local effect of differential temperature is more difficult to apply.

The methods specified in the code were not easily applicable to the bridge's complex form. Therefore, a temperature study from first principles was carried out to analyse the effect of specific plates being heated based on the sun's position throughout the year – analysing the bridge in the open and closed positions. This was conducted by heating specific elements by 13°C [2]. A temperature gradient was not applied within individual plates because no appreciable temperature difference occurs through the thickness of the plate[3].

The Lille Langebro in the open condition from the Langebro, Image: Peter Nugent

The plates to heat were determined by modelling the sun in Rhinoceros and using the rendered view to determine which plates were exposed to the sun at different times of the day and seasons of the year. This results in a temperature gradient through the cross-section which was combined with the heating and cooling of the bridge[4]. The approach was conservative, but it provided confidence in the design tolerance for the different joints along the bridge.



The architectural model of the bridge exposed to the sun to determine which plates to heat

Accidental opportunity

The bridge was due to be installed during early 2018, but an accident occurred while the spans were being loaded on to a barge, which would transport the bridge to site from the factory. The result was damage to three of the spans and no serious injuries or fatalities. The delay to the project was unfortunate but led to an opportunity to implement computational methods to produce a full shell model of a span. This was required to analyse one of the damaged spans and determine if it could be salvaged. The timeframe was incredibly short due to the contractor's lead time for ordering the steel and targeting an installation date of early 2019. The global analysis model was considered for repurposing, however the analysis software had limitations for modifying meshes. Therefore, the finite element analysis software Lusas, which uses traditional geometry and mesh objects, was used to model the span.

A similar process was carried out as described above for generating the 3D shell elements, except this time it was scripted in a parametric design tool (Grasshopper) to give greater control over the inputs. A series of Component Object Model (COM) components were developed in Visual Basic (VB) to write objects from Grasshopper to Lusas. This was achieved using an Application Programmable Interface (API) which allows communication to the parent software in a programming language. A full shell geometry, associated properties and loads were defined in Grasshopper and written automatically to Lusas saving a significant amount of time. This allowed for greater effort in investigating the representation of the impact load on the span and drawing conclusions from the analysis. The conclusions and recommendations were accepted by both the checking engineer and the client which resulted in a sizeable cost saving for the project.

Reflection

Throughout the design of the bridge there was a strong motivation by the design team to provide an elegant bridge that tied both banks of the harbour together, providing safe access for pedestrians and cyclists. This has been achieved as the bridge officially opened in August 2019 and was positively received by the city of Copenhagen. It will serve approximately 10,000 cyclists daily[5] providing a welcome addition to their city's portfolio of excellent bridges. As the bridge was very complex, traditional design methods had their shortcomings and time was therefore invested in developing an understanding of the superstructure's behaviour using nonlinear analysis – specifically to study the temperature effects and stress distribution in the superstructure. The accident during construction was unfortunate. However, it provided an opportunity to exploit new computational methods to efficiently analyse a section of the bridge, allowing it to be reused.

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[1] https://www.independent.co.uk/news/world/europe/cycling-copehagen-cycle-lanes-outnumber-cars-denmark-environment-bicycle-a7450491.html

[2] DS EN 1991-1-5 General actions – Thermal actions

[3] Emerson, Mary, The Calculation of the Distribution of Temperature in Bridges, 1973, TRRL Laboratory Report 561, Transport and Road Research Laboratory

[4] Emerson, Mary, Temperature Differences in Bridges: Basis of Design Requirements, 1977, TRRL Laboratory Report 765, Transport and Road Research Laboratory

[5] https://www.bridgeweb.com/Components-arrive-on-site-for-Copenhagen-cycle-bridge/4940