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Design and Construction of the Copenhagen Inner Harbor Mobile Bridge

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ABSTRACT:

The Inner Harbour Bridge, nicknamed the Kissing Bridge in the local press, was designed as part of an international competition for Københavns Kommune (Copenhagen City Council). Part of the development of the Inner Harbor, the new retractile bridge provides pedestrian and cyclist access across the Inderhavnen.

The bridge functions on a sliding mechanism with an opening that spans 50m, and a total length of 180m. The bridge deck is 7m wide and has a low structural profile in order to minimize obstruction to views along and across the harbour. Another significant feature of the bridge is the inclusion of viewing platforms at the edge of the navigation channel. The platforms provide a safe position for pedestrians and cyclists to view the bridge movement and be in close proximity to the passing ships and boats.

The bridge has a slightly sinuous alignment which extends the bridge and maximizes the length of the adjoining ramps. This geometry permitted the ramp grades to be limited to 4%. This grade balances the needs of the pedestrians and cyclists with the desire to limit the intrusion of the ramps onto the harbour sides.

The bridge superstructure consists of the two main cantilevered moving sections which have smooth soffits reminiscent of a boat hull. The sculptural form of the moving spans can be highlighted in a number of ways through the use of lighting or surface finishes without being obtrusive to the users or the surrounding environment. The approach ramps consist of clean box girder elements that provide an efficient structure that is elegant yet low maintenance.

Introduction

The Copenhagen Inner Harbor Mobile Bridge is a new retractile bridge that crosses the Inderhavnen and connects the Christianshavn area with Nyhavn. The Christianshavn area is increasingly popular and a residential growth area and the need for additional connectivity from this area was necessary to provide better access to the business areas to the north and west. As cyclists are a major portion of the commuting population, the Københavns Kommune (Copenhagen City Council) developed a plan for a trio of new pedestrian/cyclist bridges to increase connectivity in the area.

This paper provides an overview of the project development process, the design and the currently on-going construction. The paper discusses the main facets of the bridge but focuses mainly on the mechanism and control systems.

Project Process

The project was initiated through a design competition. The competition entrants were invited by the owner to propose on the design of the three new structures. The competition rules permitted the entrants to explore any type of mobile bridge for the three sites.

Figure 1-Project Location

The competition was advanced for two main contracts, the main Inner Harbor crossing was one contract and the two small canal bridges were another design contract. The competition entrants developed designs for each of the three crossings and were judged against specific criteria for each of the design contracts.

The competition submittal consisted of an entry summary report and supporting design drawings. The competition entries were submitted in August 2009 and judging by the competition panel initiated. The panel was composed of experts in diverse fields including engineers, architects and government officials. The panel returned questions on the competition entries and the entrants were required to respond to the questions in a project presentation to the competition panel. Subsequent to the presentations, panel convened to make their final decision for the two design contracts.

The competition jury issued it final report and decisions in October 2009. The jury selected two design teams, one for each of the design contracts. The design team led by Flint & Neill Partners, Ltd was awarded the contract for the main Inner Harbor Bridge based on the retractile bridge concept developed in conjunction with Studio Bednarksi and Hardesty & Hanover.

Bridge Concept and Design

The proposed bridges are to be located in the heart of the Danish capital, where they would be seen and used by millions, and where they would stand against a background of great beauty and historical importance. The site demanded a design with subtlety and simple elegance. The bridge needed to be graceful but demonstrate a timeless quality to continue the traditions of the Scandinavian architecture, furniture, and fashion.

The site (See **Figure** 2) called for an urban bridge that created a new public space and not merely a crossing. As a result, the team developed a structure that avoided theatrical gestures and extravagant structural forms. Such designs were considered to be too aggressive in their form and want of attention. The objective is for the bridge to provide a simple, and clean basis from which to enjoy views of the city. As a result of this objective, the team avoided masts, towers, arches or other overt structural forms, which would intrude and draw attention to themselves. This decision was not only aesthetic but also financial, as the initial conceptions using masts and towers appeared more costly that other options explored at the early phase.

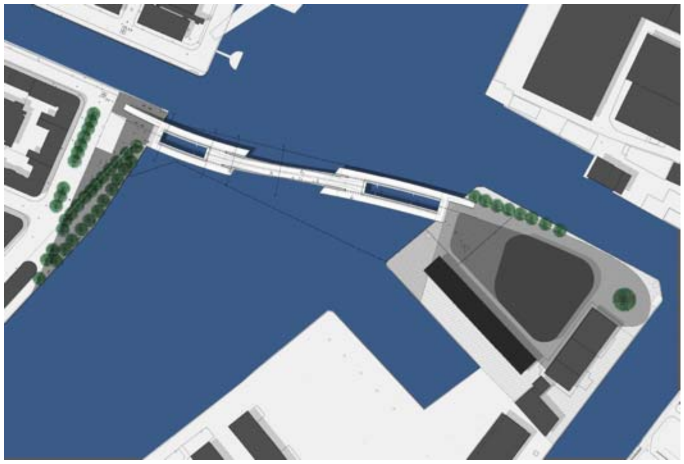

Figure 2-Bridge and Site Plan

With the context of a simple, understated form established, the team concentrated on forms that suited the site and the desired functional constraints. In keeping with the purpose of the bridge as a pedestrian structure and desire to make the bridge a new urban span, the focus of the design was on the fine detailing and finishes. The team sought to make the experience of using and observing the bridge an enjoyable one. The bridge across the Inner Harbor is new a destination from which to observe the new Theatre, Opera House and other buildings looking north towards Holmen and Langelinie, as well as south towards Christiansborg and the historic centre of the city and the nearby buildings along Nyhavn and Havnegade.

The bridge across the harbour utilizes a sliding principle for opening. The goal was to provide a refined and graceful motion. This movement was meant to complement and add to the visual character of the bridge regardless of whether it was moving or stationary. The opening section appears to float in the air as the two parts meet together at the center – a new meeting point for the bridge and visitor alike.

As part of creating a new space and a welcoming environment, the design was configured to bridge users closer to the bridge during operation. For most opening bridges the users are kept well away from where the action is, such as tall ship passing through, due to the layout of the bridge. The configuration of the Inner Harbor Bridge includes the side platforms that can remain open to use even when the bridge is in motion or open. This provides users the ability to be near to the channel as well as the bridge during operation to view the vessel and the mechanism at a much closer scale than is typical.

Overall, the design of the bridge was based in elegant simplicity and subtle sculptural forms. Goal was to produce a delightful structure which is economic and easy to build, operate and maintain.

Structural Design

This is a bridge in flight, stretching over the water and creating a new public space in the centre of the harbour. Appearing to float effortlessly, it slides gently back between the arms of the approach spans to open the channel to tall ships. Its elevational form expressions tension and the fact that it moves horizontally pulled from the rear.

This bridge creates new urban spaces. At the quays, new urban landscaped spaces provide a welcoming environment and together the bridge and quaysides become a new destination at the heart of the city, which will be a popular meeting place. The idea of a meeting place is further emphasized by the point at the centre where the two rolling halves of the bridge meet to link Amager to the City, Christianshavn to Nyhavn. The two halves recede gracefully between the two approach structures over the water to allow ships and yachts to pass.

The curved profile of the moving sections with their smooth under-bellies is reminiscent of a boat hull. By contrast, the twin approach structures at each end which embrace the moving section are more angular nature and a different color and texture to suit their secondary visual role. The main supporting piers at the edges of the navigation channel with their forward inclined legs are integral to the approach span deck and emphasize this distinction. In plan, the whole bridge is slightly curved. This adds interest and improves the experience of crossing the bridge. The maximum gradient on the bridge was set at 4% to provide easy accessibility for all bridge users. There are two areas of level deck on the approaches, one at the top of steps and the other serving also as viewing platforms to the sides of the moving deck.

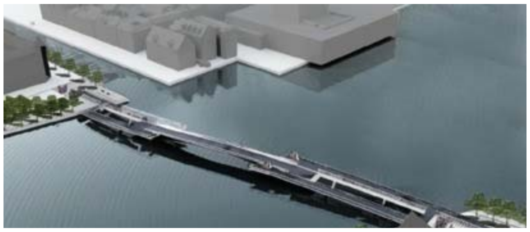

Figure 3-Bridge Closed

The moving span structure is an orthotropic box structure with a variable depth and cross section. The cross section was developed with close coordination between the structural needs and the mechanisms. The cross section transitions from a rectangular section at the toe end to a complex shape nearer to the rear. This shape provides the necessary depth for the bending moments of the structure in the global sense but also provides a trackway for the front roller wheels that provide the forward support for the span as it recedes. The structural design accounted for the static and dynamic forces especially those of pedestrians, wind and impact from vessels. For pedestrian bridges, the dynamic effects of live load must be carefully considered and Flint & Neill explored this aspect thoroughly to ensure the bridge was stable under all load conditions.

Figure 4-Bridge Open

Machinery and Electrical Design

The design of the mechanical and electrical systems utilized FEM Specifications For Heavy Lifting appliances where applicable. Due to its predominant purpose as a guide for the design of cranes and other lifting devices, the code does not directly apply to the design of movable bridge machinery. AASHTO Specifications for the Design of Movable Bridges were utilized to supplement FEM and eliminate extrapolation of the FEM requirements.

The bridge machinery is comprised of five main systems:

- Span Support Machinery
- Span Alignment and Guidance Machinery
- Span Operating Machinery
- Span Lock Machinery
- Rising Gate Machinery

Span Support Machinery

The span support machinery consists of the one Front Wheel Assembly and two Rear Wheel Load Assemblies. These three wheel assemblies provide for the support of the span loads during operation in the service position.

Each Front Wheel Assembly (See **Figure** 5) also includes the Forward Transverse guide system mounted to the wheel support. The assembly consists of:

- Central support pedestal
- Two load wheels
- Two transverse guide wheels on an equalizer frame

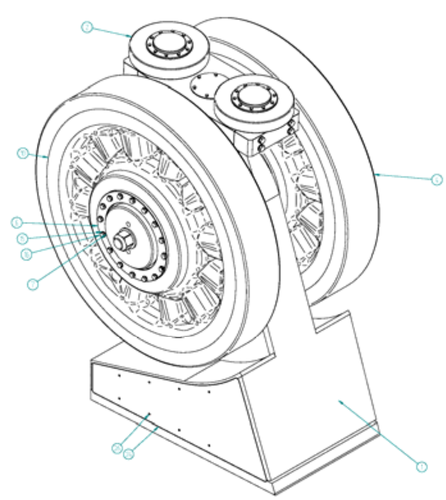

Figure 5-Front Roller and Forward Transverse Guide

The central support pedestal is a welded box with integral fixed shaft extensions. The extensions support the two load wheels. Two load wheels were used in order to account for the different radii of roll due to the curved alignment. The wheels are comprised of roller bearings in a cast hub. A high strength forged rim surrounds the hub and is connected with a shrink fit. The forged rim provides the necessary bearing strength and durability while allowing the complex wheel shape to be achieved with a casting. This minimized the machining required and the project cost. The wheel has an outer diameter of 1800 mm and a width of 280 mm.

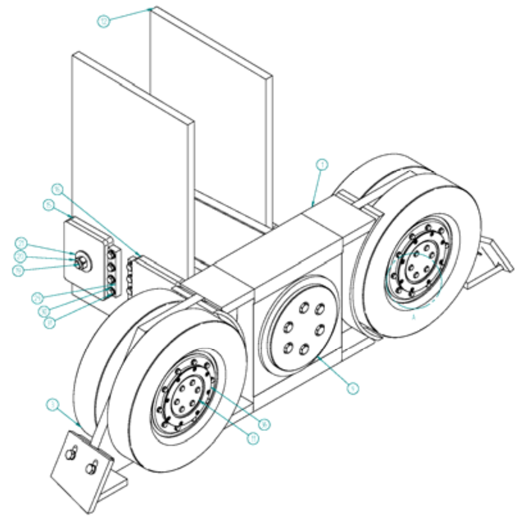

Figure 6-Rear Load Wheel Assembly

The wheels mate to a track on the underside of the mobile span structure. The track and structure is stiffened to resist the large bearing loads due to the wheel contact.

The two Rear Load Wheel assemblies are mounted to the rear of each of the movable span. For each assembly, there are two pairs of vertical load wheels on an equalizing frame (See **Figure 6**). The vertical wheels are designed to resist uplift of the tail end of the moving span, as the span is in the extended positions. The loading transitions from uplift to downward loading on the guide track as the span is retracted with respect to the forward wheels (i.e. dead load at front wheels is decreased, as rear wheels accept more load). The equalizing frame is mounted on a common shaft, and equipped with a bronze sleeve bearing. The bearing is detailed to allow movement of the equalizer frame around the equalizer shaft (rotation). The equalizing frame is restrained in the vertical axis (pitch) so that the wheels stay aligned with the track during bridge travel. Similar to the Front Wheel, the rear wheel includes pairs of wheels to account for the differing radii from the curved geometry. Each rear wheel is 455mm in diameter and 85mm wide.

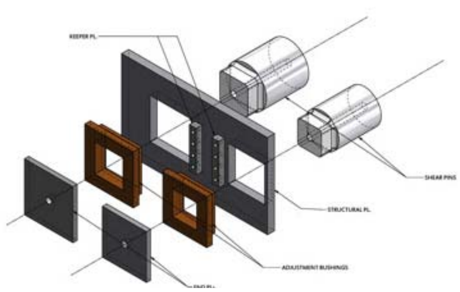

Figure 7-Pins and Bushings

The rear wheel assembly is connected to the structure utilizing pins of 142 and 120mm diameter. The pins have square machined ends that are configured to receive alignment bushings (See **Figure 7**). The bushings mate to slots in the structure webs to provide lateral adjustment during final field assembly. Vertical and angular adjustment is achieved through the bushings. In lieu of shims, a series of bushings with graduated offsets is provided. The required field alignment is achieved by utilizing the necessary bushings at each of the pins. Once the position is set, keeper plates are installed to prevent lateral movement of the bushings in the slots. The bushings include a hollow bore and are held in place by a 20mm threaded rod and cap plates. The pin connection was utilized to eliminate the need for field drilling of a substantial number of holes in the field. Due to the geometry of the structure and the channel track, access is limited at this location. The use of the pin and bushing connection facilitated the necessary operations for construction and future maintenance.

The rear wheels roll in channel shaped tracks that are fixed in the concrete approach spans. The track is channel shaped in order to provide load resistance in both the upward and downward position depending on the position of the span. The track is sloped to provide drainage for water and also includes trace heating elements to mitigate freezing in the Danish winters.

The last component of the support machinery is the live load wedges. Due to the dynamic effects of the live load on the slender structure, the design team wanted to limit the effect of these loads on the moving systems. When the span is in the closed position, the center of gravity of the span is forward of the Front Wheel support point. This results in an amplification of the loads on the Front Wheel due to the uplift at the rear wheel assemblies. Depending on the location of the applied live load, the rear wheels would see a cycle of live load that would accelerate wear of the moving components. In order to mitigate these loads, the design team opted to include live load bearings in the system. The live load bearings are wedges mounted to the top of the rear horizontal guide rollers. The wedge plate on the span mates to a similar shaped wedge plate on the fixed structure. The fixed wedge is connected to the vertical web of the channel track. For the driving force, the design team opted to again use the motion of the bridge. As the bridge nears the fully closed position, the inclined surfaces of the wedges mate and the load is transferred from the rear wheels (rolling on the top flange of the channel track) to the wedge, thus isolating the rear wheel assemblies from the live loads.

Span Alignment and Guidance Machinery
Span alignment and guidance is achieved by a system of horizontal guide rollers near the front and rear wheel locations. In addition, nose pins are provided at the toe of the mating spans.

The front roller track on the span has a central recess that receives the forward transverse guide rollers. The rollers are 480 in diameter with a contact width of 80 mm (See **Figure 5**). The wheels are mounted on an equalizer shaft to ensure load distribution. The forward transverse roller is designed to resist lateral loads due to wind on the moving leaf and keep the forward portion of the span aligned as it retracts.

An independent horizontal wheel assembly (See **Figure** 8) is detailed to provide guidance of the tail end of the bridge during travel. The horizontal wheel is designed to guide the span path against expected horizontal loads (side wind loads and curvature loads) that act upon the bridge movement. The system is also designed to absorb a limited side impact from a vessel. The horizontal guide wheel assembly consists of a horizontally mounted wheel in a welded steel support assembly. The support assembly is affixed to webs off the mobile span structure. The wheel is 400mm in diameter and 180mm wide. The roller is set with a nominal clearance of 5mm to the vertical face of the channel track.

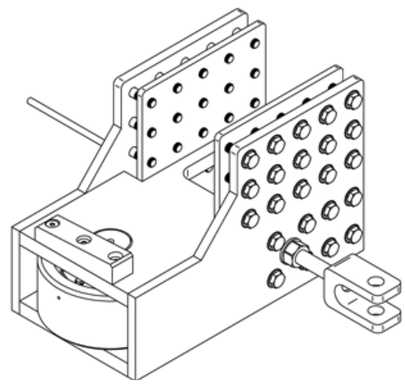

Figure 8-Rear Horizontal Wheel Assembly

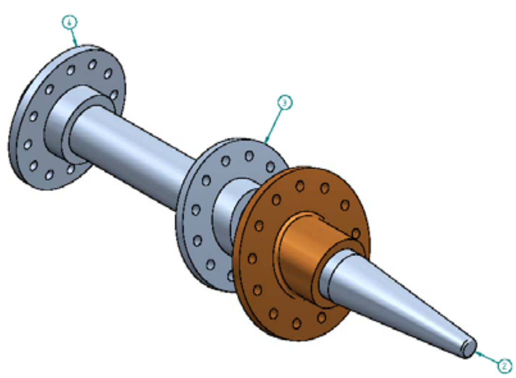

Figure 9-Nose Pins

Due to the curved geometry and the need for load transfer for the double leaf bridge, nose pins were included in the design. The limited depth of the structure at the toe (300mm) precluded the use of a driven machinery system. Rather than change the structure depth and detract from the visual character, the design team opted to utilize the bridge mechanism for the locking motion. The nose pin system (See **Figure** 9) includes a conical pin mounted in fixed front and rear hubs. The conical pin engages a receiving socket on the mating leaf. Each leaf has one pin and one receiving socket mounted on opposing corners of each span. The conical shape was selected for the uniform load capacity in all directions and also to allow a wide range of movement due to the potential deflections (span elevation and lateral misalignment) of the span while moving. The body of the bar is 127mm diameter and supplied from forged bar stock. The fixed guides are steel weldments and the receiving socket is cast bronze. Each of these components can be replaced in the future if necessary due to wear.

Span Operating Machinery
The span operating machinery is housed behind the quay walls beneath the abutment (chamber beneath grade). The operating system is a two-way rope drive system with closing and opening ropes. The operating system includes main and auxiliary motors mated to a primary reducer. The primary reducer output shafts are connected to operating drums. There are two drums for each span and the drum diameters are different to account for the different travel

speeds of each side of the span due to the curved geometry. For this bridge is was determined that synchronous movement was critical so a differential reducer was not included.

The operating machinery layout includes a motor brake at each of the motors and machinery brakes at the drums. The machinery brake is incorporated into the drum through the use of disc flange. A caliper brake engages the disc flange to provide the stopping torque required. This arrangement provides increased security in that the span can be stopped and held in position in the event of rupture in the gear train or shafting.

The closing and opening ropes are guided over a series of deviator sheaves and exit the buried chambers through a protective sleeve. The opening ropes exit the sleeve and run along the channel track and connect to the mobile span at the rear support wheels. The closing ropes run inside the fixed span structure to a deflector sheave and then connect to the mobile span

Span Locking Machinery
The Span Locking Machinery (See **Figure 10**) is mounted within the fixed concrete spans adjacent to the mobile spans. The system includes an electro-mechanical actuator connected to a rigid steel bar. The bar is 120mm square and is driven to engage a receiver mounted to the external web of the moving span. Unlike a traditional lock bar, the bar does not engage a socket. The bar acts as a stop to prevent the span from sliding open due to the gradient of the bridge. The receiver is also configured to provide a lateral bearing surface that bears on a mating surface on the forward guide of the lock bar assembly. These lateral guides are configured with a taper that engages to a nearly tight fit with the bridge fully closed. These blocks provide a means for lateral loads from wind or, more importantly, from vessel collision to be transferred directly from the moving span to the fixed approach structure without damaging the support or lateral guide wheels. The lateral load blocks also function as centering devices and aid in aligning the span upon closing.

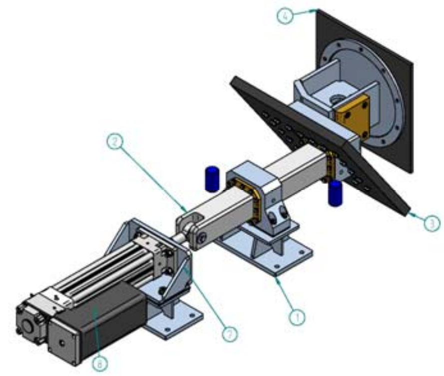

Figure 10-Span Lock and Lateral Guide Blocks

Rising Gate Machinery
As a result of the bridge design, bridge users are afforded the opportunity to be in close proximity to the leaf as it opens. The layout of the bridge required two large delineation barriers to prevent users from entering the span while it is in motion. In order to limit the impact of semaphore type gates on the visual character a system of rising gates was developed. The gates are incorporated into a slot in the deck of the fixed spans where the fixed span mates with the moving span. The gates rise out of the deck slot prior to bridge operation and prevent users from crossing onto the moving span. The gates are lifted by machinery in enclosures located at each end of the gate. The gate machinery was mounted above deck in order to facilitate future maintenance. This, however, posed an aesthetic challenge. In working closely with the architect, the machinery enclosure was designed to blend with the structure and the detail intensive railings. This limited the size of the enclosure and required a very compact drive system.

The gate machinery consists of a gearmotor with a winch that winds a Kevlar® woven belt. The belt is attached to a mounting arm from the gate structure. The gate is lifted by the spooling of the belt on the drive winch. Once the gate is fully raised, a locking pin is engaged to support the weight of the gate and any loads from users. The gate is lowered by releasing the lock pin and reversing the operation of the winch in order to allow the weight of the gate to be used to lower the gate.

Durability and Maintenance
The main challenge for the mechanisms of this unique bridge was the geometric constraints. The size of the components and their connections to the structure had to be closely coordinated through the design process. The overall design was executed with input from the structural designs as well as the architect to ensure the details served the needs of the bridge in both function and form. In addition, the owner was involved throughout the process to ensure that the systems developed included access for regular maintenance as well as future replacement for wearable components. The team utilized low maintenance components and highly durable materials to endure the harsh climate that Copenhagen presents. One example of the future maintenance considerations is the rear wheel

assemblies. The rear wheel assemblies can be fully removed for replacement with the span in the service (closed) condition. A section of the lower portion of the track is made removable since the upper portion of the channel track supports the load of the span. This provides access to remove the rear wheel assemblies for replacement or refurbishment.

Control and Power Distribution Systems
The control system for the bridge is a PLC based system with a Hot Back Up CPU and Over Watch CPU setup. The control system is utilized to govern the span movement. The two machinery systems are configured in a master-follower arrangement with the PLC responsible for motor speed control. As discussed earlier, each pair of drums is mechanically synchronized through the operating machinery. In order to monitor the span position, encoders are used at each of the operating drums. These four locations are monitored and compared to one another as well as the other span position data to ensure the four corners of the span are within the acceptable operating parameters.

The bridge is driven by electric motors at each of the operating machinery systems. The system includes four 37 kW motors with each pair configured in and A/B arrangement and operated by Variable Frequency Drives (VFD) at each drive system. The 'A' motors for each system are the primary motors used for span operation. The 'B' motors are considered the back-up motors and are exercised by the control system.

The bridge is controlled from a two story control house located adjacent to the bridge. A touch screen human machine interface (HMI) is used for all bridge controls in lieu of a large operator's desk. The control room is equipped with closed circuit television (CCTV) camera monitors to provide the operator with visual information for the main channel, the two side channels, the adjacent canals as well as the pedestrian and cyclist access areas. High mount cameras provide an overview of the bridge to ensure the safety of the public. In addition to the main HMI, the bridge is equipped with a remote HMI. The remote HMI allows the operator the option, once the main system is energized, to plug into access points at a number of locations on the structure in order to operate the bridge. In this manner, the operator can be on the approach bridge structure and directly monitor the bridge and site conditions during operations. The system is also prepared for future remote operation. Remote operation is not currently anticipated, but the owner has the option to add this function in the future as they modify the management system for the City's movable bridges along the Inderhavnen.

As with any movable bridge system design, the machinery systems had to be designed to resist the maximum potential output (stall torque) of the motors. In the case of the selected motors, this equated to approximately two hundred percent of the nominal motor torque. This value was used for the evaluation of the motors for the extreme cases of operation in accordance with the requirements of the FEM.

The bridge is serviced by a single power source from the Christianshavn side. Bridge power is carried from the service point across the channel through a submarine duct under the channel. In lieu of an onsite auxiliary generator, the design team included an auxiliary power receptacle along with a Manual Transfer Switch (MTS) at the control house. In the event of a power failure from the utility electrical service, truck mounted generators can be connected to the system and transfer switches used to operate the bridge under auxiliary power.

Figure 11-Channel Piers

Construction

Construction commenced in November 2011 with foundation work for the channel piers occurring during the harsh winter months. Final detailing and development of shop drawings occurred through the spring. The steel works and the machinery and control system development is ongoing and close coordination is occurring between the design and construction teams. The owner is playing an active role in the construction process.

Currently, the main channel piers and the buried chambers have been constructed. The contractor has constructed mock-ups of the approach span boxes to validate the intended construction sequence and the steel for the mobile spans is in fabrication. The procurement of materials and components for the machinery systems is ongoing and fabrication is commencing.

Conclusion

The Inner Harbor Mobile Bridge is a dramatic new structure being built in the beautiful city of Copenhagen. The project team's objective was to conceive a bridge that enhanced the surroundings in both function and form. Through the combined efforts of the team members, this goal has been achieved through the design phase and the conception is a testament to the creativity and ingenuity of the designers. This vision is being realized by the constructors as this iconic crossing is taking shape.

The project is currently in construction and scheduled for completion in 2013.

Figure 12-Architect's Rendering

Acknowledgements

- Københavns Kommune (Copenhagen City Council)– Owner

- Design
    - Flint & Neill Partners, Ltd.-Lead Design Consultant
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    - Speirs & Major-Project Lighting Consultant
    - COWI-Design Coordination Consultant

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    - SH Group-Machinery and Controls Contractor
    - H&C-Electrical Contractor
    - COWI-Resident Engineering and Construction Services

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