Introduction

The new Opera House in Copenhagen is built on a partly artificial island in Copenhagen Harbour facing the Royal Castle Amalienborg. The area of the site, called Dock Island, was earlier owned by the Danish Navy and the Danish Naval Shipyard. In connection with the new master plan for the location for the Opera House, Dock Island was separated by two canals into three islands, named the Central Opera Island, the South Island and the North Island as shown in Fig. 1.

All the islands were bordered with sheet walls with the South Island partially extended. The Opera Island is connected to the neighbouring islands, the South Island and the North Island by two roadway bridges crossing each canal. The remaining two roadway bridges, identified as Bridge 6 and Bridge 7 connect the city centre of Amager to the South Island and to the North Island.

To allow sailing boats to the shores along the islands the Bridge 6 is designed with a bascule span, where as the other five bridges are fixed roadway bridges. Access to the Opera Building will take place over Bridge 6 and Bridge 7 and the four bridges leading to the Opera Island from the North and the South Island. Parking areas will be provided on the neighbouring islands. Another link to the Opera Island from the Zealand mainland is planned for that will provide a pedestrian and bicycle bridge between Zealand and the South Island. This bridge will cross the navigation channel of Copenhagen Harbour and will thus be provided with a swing span or a bascule span with an opening of 35 m to give access for ships.

The design concept for all six bridges is identical with steel main girders and a timber deck structure as proposed by the architect. The acceptable depth for the main girders was limited to 800 mm due to the required clearance of 1.2 m for small boats passing under the bridges and that the fixed elevation of the bridge floor was to be kept to 2.2 m above mean water level, level with the quay floor. The length of the bridges varies between 16.4 m and 30.0 m. Bridge 1, 2 and 3 has a total width of 10.33 m, whereas Bridge 4 has a width of 15.33 m, and Bridge 6, which includes the bascule span, has a width of 10.33 m. Bridge 7, a two span bridge, has a width of 12.33 m.

The requirement from the donator, the Møller Foundation, to use only non-threatened timber species from controlled forest production resulted in an exclusion of Azobé timber from Africa for the bridge floor. Instead Danish oak from controlled production with only half the strength of Azobé was selected. This had a major influence on the structural system due to the reduced permissible span of the oak floor. In addition, the selection of steel for the main structures and timber for the bridge floor fulfilled the request for easy recycling.

The mounting of the bridges was carried out from the quay side, where the bridges were fully mounted including the timber floor before they were lifted into their final position. The bridges were all separated by bolted joints along the centre line of the bridge, except for Bridge 4, which was separated into three equally sized parts due to roadway transportation limitations. The sections were bolted together on the quay, and the complete span lifted in place (Fig. 2).

![View of Bridge 4](image)

The time schedule for the design and construction was tight. Preliminary design started January 2003, detailed design started early March 2003, and all bridges were mounted at the end of 2003. The construction of the bridges took place simultaneously with the construction of the Opera House, which is planned to be inaugurated in January 2005.

Stationary Bridges

**Bridge Main Structures**

The selection of bridge system for the five stationary bridges was primarily influenced by the following conditions:

- request for a timber deck
- the quay floor level
- required clearance under the bridges
- the flexibility to absorb sheet wall (abutment) displacements
- minimize the number of welded structural joints.

The steel structural system is built up of rolled H-sections HE800 A, B and M main girders which span the chan-
Bearings and Expansion Joints

The bearing system and the selection of bearing type were influenced by the loading conditions as well as geometrical requirement to the expansion joints above the abutments due to:

- thermal expansion of main girders
- deviation between theoretical and actual canal width after dredging the canals between the Opera Island and the adjacent island. The Bridges 1, 2, 3 and 4 were mounted before removing the soil from level +2 to −3.8 between the sheet pile walls.

A 30 mm expansion tolerance was found adequate at both bridge ends. Elastomeric fixed bearings were provided to transfer vertical and horizontal loads at each main girder end according to bridge load class 1 in the Danish Road Directorate specifications. Horizontal loads comprised braking forces in the bridge axis and wind load transverse to the bridge axis. The horizontal movements along the bridge axis were restricted by providing a horizontal bearing at each main girder bottom flange mounted with a maximum permissible slip of 20 mm to avoid any clash at bridge deck level with the abutment. Ultimately the bearings and main girders have sufficient strength to transfer the axial load due to maximum displacement of the sheet wall top, corresponding to permanent contact, i.e. no slip, in the horizontal bearings.

The bearing consists of a 50 m steel plate bolted to a cast-in device in the concrete wall and a 60 mm thick HDPE 100 plate bolted to the main girder. This system allows for a later adjustment of the slip (Fig. 5).

Bridge Deck

The bridge deck consists of Danish oak timber beams with cross sectional dimensions 241 mm by 180 mm. The beams are delivered in section lengths of approx. 2.5 m and span continuously over 4 equal spans of approx. 0.65 m (Fig. 6). The timber beam supports are provided by the main girders about 1.25 m apart and the secondary longitudinal steel H-beams arranged to reduce the timber beam span to less than 0.65 m. Originally it was planned to apply an Azobé timber beam with char-

Fig. 4: Bridge 4 plan, elevation and cross-section

Fig. 5: Abutment detail

Fig. 6: Underside of Bridge 4
characteristic bending and shear strength more than 3 times as high as those given in the Danish timber code for oak. The Azobé beams with cross sectional dimensions of 241 x 150 mm have sufficient strength to span up to 1.25 m and would not have required the secondary longitudinal girders provided due to the selection of Danish oak. In order to minimize the required number of additional longitudinal girders the actual shear strength of the oak was measured in a laboratory. This resulted in a characteristic shear strength of 4.6 MPa compared to the code value of only 3 MPa. This increase made it possible to use a centre-to-centre distance between the oak beam supports of 0.65 m. The shift to Danish oak was a result of the clients' requirement, to use only non-threatened timber species from controlled forest production.

The timber beams are fastened to the main steel girder flanges only by means of two M16 class 8.8 hot galvanized bolts, i.e. not at the secondary steel beams where only compression forces can be transferred (Fig. 7). A 5 mm EPDM (Ethylene-Propylene-Dien-Monomer), shore A60 elastomer sheet is provided between the timber beams and all steel girder top flanges to ease noise from traffic and protect the steel paint. Post-tensioning of the fastening bolts will be prescribed at certain intervals due to shrinkage and load deformations in the connections as from braking forces perpendicular to the timber beams. The deck is bordered by welded box sections alongside the deck as well as at the transition to the abutment floor. The timber beams are mounted with a gap of 4 mm which, due to the freshness of the oak, is expected to increase to 8 mm as a result of shrinkage. Filler plates of POM (Polyoxymethylene) are inserted above the steel beam flanges to distribute braking forces from wheels over more timber beam connections. All bolts are counter sunk 40 mm and sealed with Marine sealing topped by oak plugs to achieve a closed and nice-looking wooden surface. Post tensioning of the fastening bolts will be done from the underside using hydraulic tools.

**Intermediate Supports**

The design of the intermediate support for Bridge 7 was originally similar to the design for Bridge 6. However, during the excavation work for the support an old large circular granite foundation was discovered. Apparently this foundation had been used to support the pivoting bearing of an old swing bridge. It was decided to preserve the old foundation, and consequently the intermediate support had to be redesigned. The steel superstructure is supported by 2-Ø 800 mm steel piles with a 15 mm wall thickness, one placed on either side of the old foundation. For aesthetical reasons each steel pile has been provided with a concrete cap.

**Bascule Bridge**

**System**

Bridge 6, which spans the 27 m wide inner navigation channel with mooring quays for yachts, comprises a simply-supported 16.32 m span and the 14.52 m bascule span (Figs. 8 and 9). In the service condition of the bridge the hydraulic cylinder provided for lifting the span is inactive, so that the bascule span is simply supported on the intermediate support in the channel and on the rotation bearing which connects the main girders to the rear supports in the concrete caisson behind the sheet.
pile wall. The total width of the bridge is 10.33 m. The lateral displacement of the fixed span is limited to 15 mm controlled by means of a fixed support (shear locks) arranged in the centreline of the bridge on the intermediate support and on the quay abutment. This fixation with limited lateral movement is required to assure fitting between the fixed span and the bascule span at the interface bearings during lowering and opening of the span.

Hydraulic Concept and Operation

For aesthetical reasons any lifting equipment, counterweight or structure could not be visible above deck/quay level. The bascule span is lifted by means of two hydraulic cylinders placed in a caisson behind the South Island quay wall. A counterweight to reduce the lifting force is not used because it was determined to be more economical to apply larger cylinders and minimize the size of the caisson.

The cylinder bore is 280 mm, the stroke is 2800 mm and the design pressure is 250 bar. The maximum design cylinder thrust force is approximately 1600 kN per cylinder. It has been assumed that the bascule may be operated at a design wind speed of maximum 16 m/s. The machinery including hydraulic pumps etc. is placed in a waterproof steel box located in the caisson.

The bridge is operated only by authorized personnel, i.e. a "Bridge Guard". When a ship wants to pass through, the Bridge Guard fences off the bridge deck by means of chains, and then operates the hydraulics by a portable control panel. This simple and safe procedure is justified when considering the low expected frequency of vessel traffic.

Bridge Main Structure

The bridge main structure is conceptually similar to the stationary Bridges 1, 2, 3, 4 and 7. However, the interface between the bascule span and the fixed span called for modifications to provide support for the bascule span on brackets attached to the fixed span, and a shear lock between the bascule and fixed span. Modification has also been implemented at the bascule support end to assimilate the concentrated load from the two hydraulic cylinders in the bridge main structure. Two 50 mm thick plates connect the bearing points and transfer in-plane loads to the transverse beams and a heavy welded box girder joining the bearing plates above the two rotation bearings. The application of only two hydraulic cylinders with a distance of 2380 mm to the rotation bearing has contributed considerably to the simplicity in construction and operation of the bascule span.

Bridge Deck

The bridge deck for the Bascule Bridge is an identical timber beam solution as applied on the other stationary bridges. The dead weight of the structure is sufficient to counteract extreme wind conditions to prevent any overturning of the Bascule span in the open condition, which means that no tensile forces will occur in the hydraulic cylinders.

Caisson

The support for the bascule span on the South Island is designed as a deep caisson which also accommodates the machinery and equipment for the bridge operation. The caisson is constructed in a sheet piled cofferdam behind the South Island quay wall. The concrete from level -5.0 to -1.7 was cast under water. This mass of concrete stabilized the cofferdam, which was then drained. The rest of the work, including caisson floor, concrete wall-lining and support plinths was carried out underwater.

Flooding of the caisson during high water is acceptable; also the bridge deck above the caisson is not watertight. Therefore all installations in the caisson are designed to be waterproof.

Intermediate Support

The intermediate support consists of a 1.5 m x 1.2 m concrete beam, 8.7 m long, supported by 4-0.800 mm steel piles with a 15 mm wall thickness. The piles are driven 12 m into the seabed, the last 1 m into limestone. The piles are filled with concrete. The piles are fixed in the seabed; the design conditions and calculation of the fixity was verified by an actual load and deflection test. The concrete beam, as shown on Fig. 10 was precast onshore and lifted onto the piles and connected with grout. To protect the intermediate support from ship collision, a fender and guide structure of steel piles driven into the seabed and wooden bumpers is used (Fig. 11).

Fabrication and Erection

The bridge steel grids were fabricated in 5 m wide full length sections in the workshop. The floor beams in oak were mounted in the shop on the bridge grid top flanges. The fully mounted section with a total weight of approximately 105 t was transported by lorry about 200 km from the shop to the site. The erection was carried out by means of two mobile cranes from the quayside. Bridges 1 to 4 were mounted before excavation of the North Channel and the South Channel took place. Displacement of the abutment on the sheet pile walls in the bridge axis due

![Fig. 10: Intermediate support of Bridge 6](image-url)
Fig. 11: View of Bridge 6 – opening in front of the New Opera House

to relief of earth pressure from the canal side when canal gravel fill was removed had to be considered when adapting the length of the bridge segments. The bridge segments were mutually connected via butt plate joints in the cross girders 2.2 m apart. The fabrication of the steel structures started in July 2003 and the first bridge was mounted at the end of September. Bridge 4 was mounted at the end of December 2003 as the last bridge. The construction schedule for the bridges was very tight but necessary in order to keep to the overall time schedule for the Opera project with the completion of the entire complex by early October 2004.

Conclusion

The six Dock Island Bridges were designed to conform with strict requirements to construction height, architects’ aesthetical expectations, and adaptation to existing and new quay configurations. Further the construction solutions should adhere to the client’s requirements to sustainability and use of non-threatened material species. This request led to leaving out the application of Azobé timber for the bridge floor and selecting Danish oak timber with only half the strength of Azobé. The reduced permissible span of the oak floor beams compared with Azobé and the limited depth available for the timber beams had a major influence on the selected concept for the steel structural system. The selection of steel material, all in S355, for the structures and timber for the floor fulfilled the requirement of ease in recycling.

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