Recent Trend Marking Applications of Major Steel Structures in Denmark

Kjeld Thomsen, Man.Dir., M.Sc.
ISC Consulting Engineers Ltd.
Copenhagen, Denmark

Abstract

The present paper describes new developments and special features related to major steel structures recently built or under construction in Denmark, ranging from buildings and offshore structures to some of the world’s largest bridges.

Advanced joint technology, weldable high strength steel, innovative transport and mounting technology, alternative corrosion protection method have been applied and largely influenced design and construction.

1. Introduction

The development of high capacity transport and lift equipment, such as floating cranes for offshore application and hydraulic cranes onshore, has largely affected construction methodology in recent years and lead to manufacturing of still bigger and heavier welded elements in the workshop for full size transport and erection.

The offshore industry has pioneered this development and now handles lifts from 5,000 to 10,000 t. For multispans bridges erection time is reduced by full span mounting, procedures well known from the Great Belt bridge and the Northumberland bridge [1] with lifts up to 8,200 t and will as well be used at the Øresund Link now under construction.

Durable corrosion protection of steel structures by painting systems often amounts to more than 15% of the unit price of the structure. A substantial cost saving has been achieved by replacing painting inside closed box girders and box members with a dehumidification system. This is for instance the case in the Great Belt east bridge, the Farø bridge, and the coming Øresund Link bridge.
High strength weldable fine grain steel qualities with yield stress up to 460 N/mm² and adequate fatigue strength have improved economy and design of long span structures and are widely used for the Great Belt bridge and the Öresund Link as well as in high rise office buildings.

The improvement of computer capacity and FEM analysis software has made more refined analysis and hot spot determination a routine in engineering practice for refinement and optimization of structures subject to fatigue due to for instance railway loading and wave loads offshore.

The tendency to select slender structural concepts for long span structures increases the sensibility to structural vibrations from wind and dynamic loads. Rational methods to provide structural damping therefore form part of economic structural concepts, for instance in cable stayed bridges, in slender girder bridges, and in tall steel chimneys.

The above mentioned issues will be further discussed in relation to outstanding structures in Denmark to which they have had a decisive influence.

2. Water Tower, Tyrsted

The 2000 m³ volume water tower in steel at Tyrsted, Denmark [2], turned out to be cheaper than the conical shell type water tower in concrete of which a large number has been built during the last 30 years. The octagonal form of the center column and the tubular columns in the conical fan match the geometry of the elevated tank, shaped like a cut diamond. The tower is 28 m high with a max. diameter of the tank of 25.2 m. The tank is supported on a 15.75 m long centre column with octagonal shaped box section and side length 1165 mm, matching the shape of the bottom of the water tank.

The tank is built up of plate panels provided with interior longitudinal and transverse stiffeners in a narrow mesh to provide sufficient strength towards inplane forces and the up to 130 KN/m² vertical load at the tank bottom.

To reduce the size of the stiffeners, intermediate support of the plate panels is arranged at three levels by means of star shaped bracing.

![Figure 1. 2000 m³ water tower in steel at Tyrsted, Denmark](image)
systems. Features of special interest to be mentioned are:

- Dynamical behaviour of system with full tank.
- Erection concept.
- FEM analysis of bracing joints.

The fan column system produces a certain restraint of the tank and thereby causes substantial reduction of the free bending moments, the lateral deflection and the buckling length of the centre column. As the impact factor to be considered for gust wind reaches 6.7 due to a rather low frequency for the first mode of natural vibration, this interaction has substantial effect on the dimensions of the plates in the centre column.

The tank was built up of prefabricated welded panels on the site, as the size made roadway transport impossible. The 16 m long centre column and the 21 m long tubular fan columns were shop fabricated to permanent size.

The erection of the tank was carried out by means of four 125 t capacity mobile cranes. Four pad eyes were provided on the tank for the lift. The 16 m long centre column was lifted simultaneously from horizontal position by means of a wire sling suspended from the tank top through the centre tube to the column top. From the airborne position the centre column was lowered onto the anchor bolts on plate chocks on the foundation and the anchor bolts were tightened. Thereafter the tank was lowered to the column top and the bolted butt joint connected with HSFG bolts, class 10.9. The fan columns were moved sideways into the permanent position and connected with the tank and the foundation by means of bolted butt plate joints.

3. The Öresund Link - Two Level Bridge

Sweden and Denmark are being joined across the Öresund by a road and rail link with a sequence of a bridge, an artificial island, and a tunnel giving a total length of 15.4 km.

The bridge with a total length of 7.8 km will be the largest railway bridge in the world.

309
The cable stayed navigation span crossing Flintrännan is 490 m, and typical approach spans are 140 m. Along its full length the superstructure consists of 10.2 m high twin steel truss girders acting compositely with a concrete roadway deck on their top chords.

The two railway tracks are carried inside the trusses at the level of the bottom chord on a double channel concrete girder. Construction started in July 1996, and completion is scheduled in the year 2000.

The western approach spans with a total length of 3,014 m consist of 22 spans of which 18 are approx. 140 m long, and 4 are approx. 120 m long. The length is divided into two expansion sections with the structure continuous within each section.

The eastern approach spans with a total length of 3,739 m consist of a total of 27 spans of which 24 are approx. 140 m long, and 3 are approx. 120 m long. The length is divided into three expansion sections continuous within each section.

Figure 3. Öresund Bridge. Computer visualization

Some key features of the bridge concept, which is described in details in [3], shall be highlighted:
The warren type trusses have inclination of diagonals of 45° corresponding to 7 bays of 20 m. A more open spacing than is generally applied.

- The chords and lattice members are all welded box sections with a width of 1.3 m, a lattice member depth of 1.0 m and a chord depth of 1.5 m. Corrosion protection of the interior of the box sections has throughout been solved by means of dehumidification.

- High tensile steel qualities of the thermomechanical types S460ML and S460M, covered by the Eurocodes, with a yield stress of 460 N/mm² are applied in up to 60 mm thick plates. These steels have fine grained material composition and good welding properties. The only drawback is, that these steels do not regain their additional strength when having been subjected to long exposure to fire.

- The Harp type configuration of the cable stay system is harmonized with the inclination of the diagonals. The uniform inclination of all diagonals in the approach spans is substituted by a “skew” arrangement with long diagonals in the direction of the stays and short diagonals in between.

The 490 m cable stay span is the largest in the world for a bridge which carries both roadway and railway traffic.

The 203.5 m high pylons are designed as free standing columns in concrete without any cross beam connections above the bridge deck.

The construction of the approach spans will be based upon sea transport and mounting of full 140 m spans with a dead load of more than 5000 t taking advantage of high lift capacity at hand for offshore cranes.

The design of the bridge is carried out neither to Swedish nor to Danish standard, but according to the Eurocode system and a specially developed Project Application Document (PAD), reflecting the Scandinavian safety approach.
4. New Swing Bridge, Næstved

The new swing bridge at Ydernæs on Zealand in Denmark [4] shall carry the new by-pass road around the city of Næstved over the 44 m wide navigation channel, connecting the city of Næstved with the sea. The surroundings along the channel and its continuation in the Suså creek are attractive leisure areas for pedestrians, bikers, and canoe traffic.

The bridge alignment is straight crossing the centre line of the channel in an angle of 80°. In the closed condition the bridge is continuous with one main span of 58.9 m and two side spans of 19.5 m each. The main supports for the two rotating bridge sections are located at the channel shores, 58.9 m apart and 19.5 m from the end abutments.

The steel superstructure consists of two 48.95 m long rotatable sections with a bridge deck shaped as a parallelogram with edges parallel with the channel direction. Due to the skew crossing, no additional cut off is required in the end corners of the deck to allow anti-clockwise opening of the two bridge sections. The rotating sections are supported on circular 5 m dia. roller bearing slew ing rings, arranged on tubular shaped concrete supports with a mutual free distance of 50 m, measured perpendicularly to the channel.

The span length of the side spans has been chosen partly to limit the overturning mo-ment on the circular roller bearings, and partly to allow a direct straight passing of the existing rooad on the southern channel shore.

The bridge superstructure is hinged at the centre by means of two hydraulic aktivitated pins and fixed at the shore supports on the roller bearings. At the abutments each girder end has two hydraulic activated pins.

At the girder ends, counterweights of iron filled concrete are cast inside the bridge girder sections to establish balance for the permanent load and thereby minimizing the overturning moment on the roller bearing support under opening and closing conditions.

Figure 5. New swing bridge crossing Næstved navigation channel. Elevation and plan
The two bridge sections are both welded and built up as 6 m wide box sections supporting an orthotropic steel deck plate. Outside the box girder webs the deck is supported on 3.5 m long cantilevered plate girders, tapered towards the edge beam which is formed as a welded hollow section carrying the parapets.

The box girder depth varies from 3.5 m above the roller bearing support to 1.5 m at the bridge centre and at the abutments. Transverse full size plate diaphragms at 4.0 m distance are provided perpendicularly to the bridge axes in plane with the cantilevered cross girders.

Several outstanding features can be highlighted for the swing bridge:

- Price competitive compared with other bridge concepts, such as hoist bridges, bascule bridges, and cable stayed bascule bridges.

- Adaptability of the bridge concept to the environment, preserving shore continuity, and a smooth integration in the landscape in general.

- The steel superstructure consisting of two equal sized rotating elements formed as box girders with variable heights is efficiently adapted to the circular supports consisting of cylindrical shaped concrete pier shafts.
The bridge concept incorporates a new simple mechanical system comprising the roller bearing supports on the piers and a horizontal centre pin connection providing continuity for the traffic service loads.

The closed contour of the bridge girder and the cylindrical piers housing the mechanical and electrical installations leads to a durable and low cost maintenance solution.

Corrosion protection inside the box section will be provided by means of a dehumidification system.

The two bridge sections are transported from a shop in Poland fully mounted with the roller bearing on a barge. Beams with teflon sliding pads will be arranged between the barge and the pier. The bridge sections are then pulled sideways over the beams to the pier and lowered to final position on pier tops by means of hydraulic jacks.

5. Star Offshore Platform Concept

The star platform has been developed by Maersk Oil & Gas for marginal oil fields in the Danish North Sea. The star platform consists of only one central tubular column of 3 m dia. above the water surface contrary to conventional platforms with 4 or more legs. Below the water level the central column is fixed to a triangular bracing 120° apart containing template pipes for the anchor piles driven approx. 40 m into the subsoil. The star platform is designed for a topside load of up to 700 t and approx. 45 m water depth. The star concept has been very successful and feasible and so far a total of 5 platforms has been installed in the Danish North Sea. Features to be highlighted are:

- Adequate for support of minor process topside modules, accommodation modules, and as simple support for bridge process modules.
- Easy and fast installation with only one welded joint to be carried out offshore between a tube stub between the topside module and the central star tube. Two offshore lifts are required, one for the prefabricated star and one for the prefabricated topside structure.

Figure 6. Star platform in the Danish North Sea
• The star platforms are remote controlled from a mother platform and connected with a subsea pipeline to a major production platform.

• Fairly easy to dismantle for use in a new location.

The recent extension of the Skjold Field comprised one star platform with accommodation module and Helideck connected with a 100 m long bridge to the mother platform, and one star platform connected to the mother platform with a 50 m long bridge process module comprising two decks.

![Star platforms in the Skjold Field](image)

**Figure 7. Star platforms in the Skjold Field**

7. The Great Belt, East Bridge

The 6.8 km long Great Belt east bridge [5] includes a suspension span of 1.624 m with a free height of 65 m above sea level, and side spans of 535 m each. The continuous approach bridges with spans of 193 m, total approx. 2.5 km and 1.5 km, respectively on the west and east side. Apart from being the second largest bridge span in the world, after the Akashi bridge in Japan with 1990 m centre span, some interesting features are worthwhile mentioning:

• The 31 m wide and 4 m deep box girder will be the largest slender box girder ever built.

• Hydraulic buffers are arranged between the anchor block and the girder which allows slow movements up to \( \pm 1 \) m whereas load induced rapid movements are restrained by proper tuning of the dampers.

• The continuity of the girder through the towers improves the overall stiffness of the system and also improve the aerodynamic stability.
Figure 8. Great Belt east bridge elevation

The approach bridge superstructure with continuous spans of 193 m are 31 m wide and 6.7 m deep box sections with constant height. Some features are worthwhile mentioning:

- The relatively slender box girder reached sufficient strength by applying high strength weldable steel S460 in the box and up to 50 mm plate thickness near the supports.

- Wind tunnel test revealed that the approach spans would be subject to unacceptable oscillations in wind speeds above 20 m/second when congested with queues of vehicles. Therefore a tuned mass damper system had to be installed in the spans for protection against detrimental wind induced oscillations. The damper will ensure damping of vibrations at wind speeds below 25 m/second.

Figure 9. Great Belt east bridge. Erection of 193 m long approach span
The erection of the approach spans followed the concept applied on the Farö bridge and the Great Belt west bridge. Full spans were sea transported on barge from an assembly yard in Aalborg, 225 km away, to the site and the 2,500 t heavy units lifted onto the pier supports by means of floating cranes.

Hogging moments were introduced at the supports to obtain effective continuity also for the dead load of the bridge. The procedure applied was to weld the joint above the support with a certain gap of the free end. After welding the free end was lowered to the permanent position on the bearings.

The corrosion protection of the interior of the whole length of bridge box girders is achieved by installation of an adequate number of dehumidification systems.

8. 350 MW Boiler Building Vestkraft

The new boiler building for extension of the Vestkraft power station in the city of Esbjerg [6], Denmark’s offshore base, is typical for the present state of the art. The 78 m tall braced frame structure, supporting the 3,600 t boiler, comprises a total of 4,000 t of structural steel. The construction concept is based on the idea of full prefabrication of elements and elimination of welding and welding control on site.

- All members are selected with bolted joints adequate for fast assembly.

- All elements are fabricated as straight members with bolt holes made on automatic PNC controlled drilling equipment.

- Elements are adequate for compact transport on lorries to site.

- Erection is carried out by means of mobile cranes supplied with a stationary tower slewing crane and a minimum of labour resources on site. The present structure required mounting of 40,000 structural bolts.

Figure 10. 350 MW boiler building structure in steel during erection
Corrosion protection of the prefabricated straight sections was carried out in an automatic cleaning and painting shop before delivery. Only minor repairs had to be carried out after erection.

Figure 11. 350 MW boiler building structure. Typical bolted joint

References

[1] Swan Russ,
Northumberland Strait Bridge.
Bridge Design and Engineering 1.

[2] Thomsen Kjeld,
Water Tower at Tyrsted, Denmark.
IABSE Proceedings P-79
Nov. 1984

[3] Thomsen Kjeld, Nissen Jørgen, and
Gimsing N. & J.,
The Öresund Bridge
IABSE 15th Congress.
June 1996, Copenhagen, Denmark.
