Orthotropic Design Meets Cold Weather Challenges

An Overview of Orthotropic Steel Deck Bridges in Cold Regions

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Introduction

Initially developed by German engineers following World War II, orthotropic bridge design was a creative response to material shortages during the post-war period. Lightweight orthotropic steel bridge decks not only offered excellent structural characteristics, but were also economical to build (Troitsky 1987). Moreover, they could be built in cold climates at any time of the year. Engineers from around the world utilize this practical and economic system for all types of bridges. While concrete must be at or above 5 degrees Celsius to properly cure, it is physically possible to encapsulate and heat the concrete construction process; admittedly, this adds to construction costs (Mangus 1988), (Mangus 1991).

Orthotropic steel deck bridges have proven to be durable in cold regions. The orthotropic steel deck integrates the driving surface as part of the superstructure, and has the lowest total mass of any practicable system. In Europe, where the advantages of orthotropic design have been embraced with enthusiasm, there are more than 1,000 orthotropic steel deck bridges. In all of North America, there are fewer than 100 bridges of orthotropic design.

This article will give an overview of imaginative steel deck bridges currently in operation in Norway, Russia, Sweden, and Ukraine. The examples cover a matrix of rib types, superstructure types and various bridge types. Russia has developed a mass manufactured panelized orthotropic deck system and has devised special launching methods for cold regions. Russian engineers prefer the open rib design and have industrialized this system, while most other engineers prefer the closed rib. Researchers, as well as the owners of orthotropic steel deck bridges, continue to monitor the performance of various rib types (Figure 1).

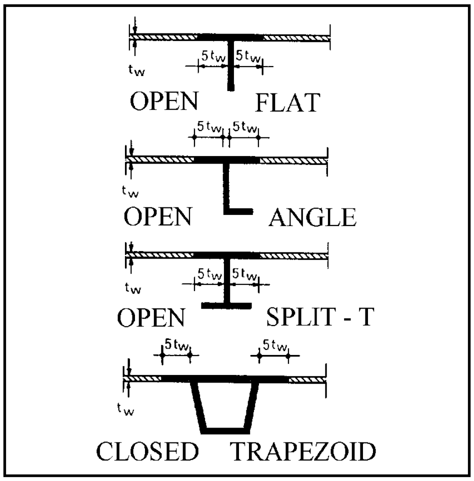

Figure 1. Rib designs.

In Norway

Nordhordland Floating Bridge

The Nordhordland Bridge across the Salhus fjord is Norway's second floating bridge and the world's largest floating bridge (Meaas, Lande, and Vindoy, 1994). The bridge was opened for traffic in 1994. The total bridge length is 1615 m and consists of a high level 369 m long cable stayed bridge and a 1246 m long floating bridge (Figure 2). The floating bridge consists of a steel box girder, which is supported on ten concrete pontoons and connected to abutments with transition elements in forged steel. The main elements are a high-level cable stayed bridge providing a ship channel and a floating bridge between the underwater rock Klauvaskallen and the other side of the fjord. The cable stayed bridge provides a clear ship channel. A 350 m long ramp is required to transition from the higher bridge deck on the cable

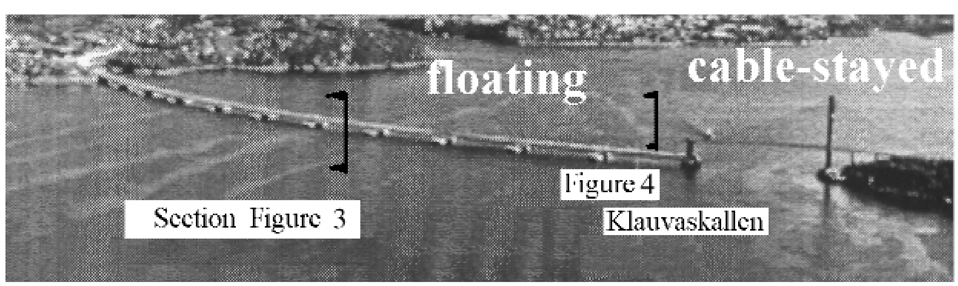

Figure 2. Nordhordland Floating Bridge across Salhus fjord of Norway.

stayed bridge to the bridge deck 11 m above the waterline. The steel box girder of the floating bridge forms a circular arch with a radius of 1,700 m in the horizontal plane. The supporting pontoons are positioned with a center distance of 113 m and act as elastic supports for the girder, which is designed without internal hinges. The bridge follows the tidal variations by elastic deformations of the girder.

The steel box girder is the main load-carrying element of the bridge (Figure 3). The octagon girder is 5.5 m high and 13 m wide. The free height below the girder down to the waterline is 5.5 m and this allows for passage of small boats. The plate thickness varies from 14 mm to 20 mm. The plate stiffeners are in the traditional trapezoidal shape and they span in the longitudinal direction of the girder. The stiffeners are supported by cross-frames with center distance of maximum 4.5 m. At the supports on the pontoons, bulkheads are used instead of cross-frames. This is done because the loads in these sections are significantly larger than in the cross-frames. The plate thickness

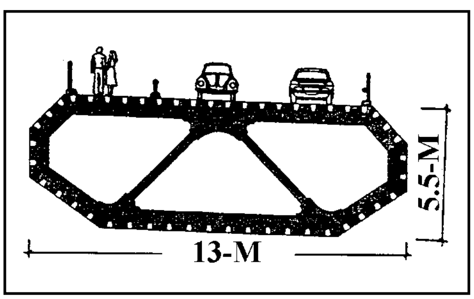

Figure 3. Nordhordland Floating Bridge.

in the bulkheads varies from 8 mm to 50 mm. The box girder is constructed in straight elements with lengths varying from 35 m to 42 m. The elements are welded together with a skew angle of 1.2° to 1.3° to accommodate the arch curvature in the horizontal plane. The cross section dimensions of the octagonal box girder are constant for the length of the bridge.

The stress level varies significantly over the length of the bridge. In the areas with the highest stresses, steel with a yield strength of 540 MPa is used.

Orthotropic bridge design was a creative response to material shortages during the postwar period

In the remainder of the bridge (in the cross-frames and bulkheads) normalized steel with yield strength of 355 MPa is used. The total steel weight of the box girder is 12,500 tons, of which approximately 3,000 tons are high strength steel. The elevated ramp is approximately 350 m long and has a grade of 5.7 percent (Figure 4). The elevated ramp is constructed with an orthotropic plate deck 12 mm thick and has 8 mm and 10 mm thick trapezoidal ribs 800 mm deep. T-shaped crossbeams support the ribs with a maximum center distance of 4.5 m. The main 1,200 mm deep box girders are located one at each edge of the ramp in order to maximize the stiffness about a vertical axis. The steel weight of the ramp is 1,600 tons.

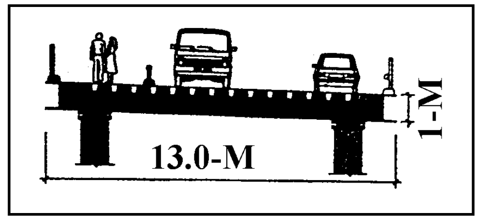

Figure 4. Nordhordland Floating Bridge.

Bybrua Bridge

The Bybrua cable stayed bridge has a main span of 185 m. The 15.5 m wide roadway superstructure was fabricated in the shop in 9.0 m sections (Figure 5). There is a combined pedestrian plus bicycles area on each side of the three traffic lanes. The cross section of the main span has a deck-plate 12 mm thick, but this increases to 16 and 20 mm at the cable anchorage. The bottom plate varies between 8 mm and 10 mm thickness, and the webs between 12 mm and 20 mm. At intervals of 3.0 m there are frames supporting the longitudinal stiffening system. In the bridge deck this is made up of standard trapezoidal ribs

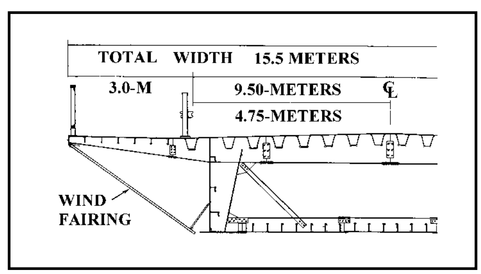

Figure 5. Bybrua Bridge.

from the German steel company Krupp, and in the bottom flange box section of bulb flats open ribs were utilized (Aune and Holand 1981). In the longitudinal direction the deck was divided into six fabricated sections, two of which were welded to the web sections. The box bottom was fabricated as three sections. The total steel weight is about 1,100 tons. All elements prefabricated in the shop were welded, as were the field splices in the deck, whereas "Huck" high tensile bolts were used in all other field joints. All field joints were calculated as friction connections. The whole steel structure is metallized with zinc and painted according to the specifications of the Norwegian Public Roads Administration. The superstructure received the maximum live load stresses during the erection of the bridge. The wearing surface of the bridge deck is the same as that developed by the Danish State Road Laboratories for the Lillebelt Bridge of Denmark.

Storda and Bomla Bridges

The "Triangle Link" project connects three islands off the Norwegian coast south of Belgen to the mainland with three bridges (Larson and Valen

Researchers continue to monitor the performance of various rib types

2000). The entire project was completed in April 2001. The two orthotropic steel deck suspension bridges are known as the Storda Bridge and the Bomla Bridge. The Storda Bridge is 1,076 m long, has a main span of 677 m, with towers 97 m high and a vertical clearance of 18 m (Figure 6). The Bomla Bridge is 990 m long with a main span of 577 m and the tower height is 105 m. The roadway of both bridges is 9.7 m wide. Scanbridge AS of Norway fabricated the Bomla Bridge's steel approach superstructure, which was launched out over the tops of the columns from the shore. The steel components for the main span superstructure of the Storda Bridge were prefabricated in the Netherlands (Figure 6) and the main span superstructure of the Bomla Bridge was prefabricated in Italy. The orthotropic ribs for the Storda Bridge were prefabricated in France. The orthotropic sections were transported to the site by barge, and were lifted into position by a crane.

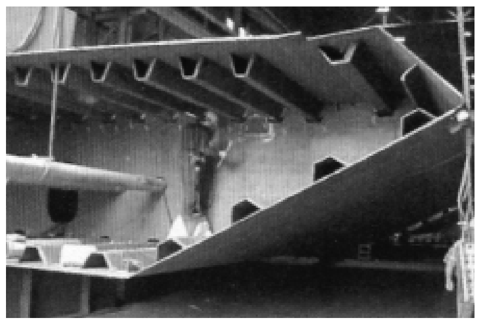

Figure 6. Storda Bridge.

In Russia

Russian engineers have standardized their orthotropic deck plates using open or flat plate ribs as shown in Figure 1. They have several launching solutions or standardized methods for pushing the superstructure across a river or gorge. There are a limited number of bridge case histories documented in English, but they provide an overall view of Russian techniques (Blank, Popov, and Seliverstov 1999). In the city of Arkhangel, Russia, a vertical lift record span bridge of 120.45 m was completed in 1990 (Stepanov 1991). The Berezhkovsky twin parallel bridges are multi-cell box girder bridges consisting of three spans of 110 m + 144.5 m +110 m. Each bridge has four traffic lanes 3.75 m wide. These bridges were the first to be launched with inclined webs (Surovtsev, Pimenov, Seliverstov, and Iourkine 2000).

Oka Bridge

The four-lane orthotropic twin box girder bridge crossing the Oka River on the bypass freeway around the city of Gorki, Russia, was opened to traffic in 1991 (Figure 7). The 966 m long superstructure consists of 2 spans x 84 m + 5 spans x 126 m + 2 spans x 84 m (Design Institute Giprotransmost 1991). This bridge is a single continuous superstructure with a fixed bearing 420 m away from one of the abutments. The total bridge width (29.5 m including steel traffic barriers) provides two sidewalks 1.5 m wide each, four traffic lanes, four safety shoulders and a center median. The total weight of steel for the superstructure is 10,635 tons, or 373 kg/m2. The orthotropic steel superstructure comprises five basic elements (Figure 7). There are two main box girders assembled from two L-shaped sections for the bottom face and sides. The intermediate orthotropic plate sections were used for the top flange of the two box girders, as well as the majority of the deck. The end sections of the orthotropic plate were panelized with tapered ends, because only sidewalk loading is required. The transverse diaphragms are steel trusses between the box girders. The diaphragms required extra steel beams at the bottom flange of the box girder above the bearings. The main box girder was shop fabricated in L-shaped sections that are 21 m long and 3.6 m deep. The intermediate orthotropic welded steel deck plate was shop fabricated in panelized sections 2.5 m wide and 11.5 m long.

The longitudinal ribs of the orthotropic deck and steel box girders are flat rib plates spaced at 0.35 m, and the spacing of transverse ribs is 3.0 m for both components. The stiffening ribs of the main girder are located on both sides of every web. The vertical split-T ribs of the box girders were aligned with the transverse ribs of the ribbed plate, thus creating the integral internal diaphragms. The longitudinal stiffening ribs are at a constant spacing

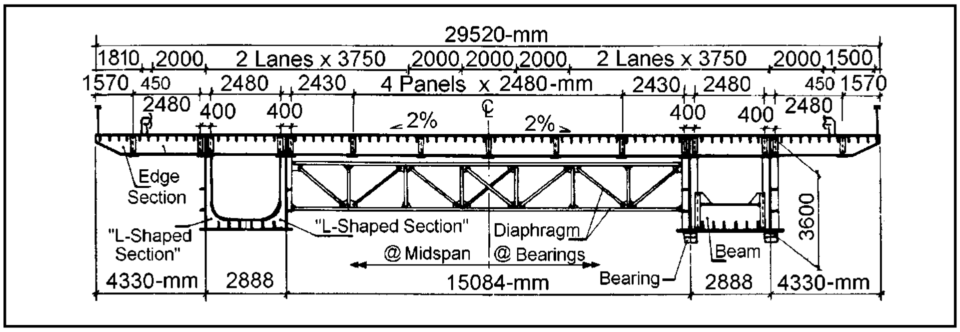

Figure 7. Twin box girder bridge crossing the Oka River, Russia (split–section).

along the bridge. Depending on the web thickness, additional vertical stiffening ribs were required between the diaphragms. The superstructure was erected using “continuous launching” from one bank of the Oka River. The shop-fabricated elements were added piece by piece to form a continuous structure at the “erection slip” area on this riverbank. The joints of the horizontal sections of the orthotropic deck and ribbed plates, as well as the joints of the web of the main girder, were automatically welded. The joints of the longitudinal ribs of the ribbed plate were manually welded. All the remaining joints used high strength bolts.

In Sweden

High Coast Suspension Bridge

The High Coast Suspension Bridge of Sweden is almost the same size as San Francisco’s Golden Gate Bridge (Merging with Nature 1998). The main span is 1,210 m long with suspended

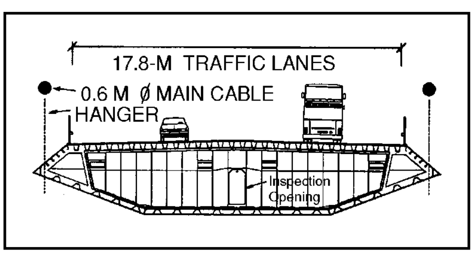

Figure 8. High Coast, Sweden, section.

side spans of 310 m and 280 m. The width of the roadway is 17.8 m, allowing for a possible future extension to 4 lanes (Figure 8). The distance between the main cables is 20.8 m and there are 20 m between the hangers. The girder is continuous through the towers extending 1,800 m from abutment to abutment where expansion joints and hydraulic buffers are located. The 48 box girder sections were fabricated at a shipyard in Finland (Pedersen 1997). The standard section is 20 m long with two

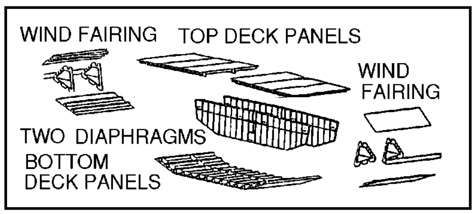

Figure 9. High Coast, Sweden components.

sets of hangers each and weighs 320 tons (Figure 9). The 20 m long panels for the deck, sides and bottom were fabricated with a maximum width of 10 m. They were fabricated from steel plates, typically 9 to 14 mm thick,10 m long and 3 to 3.3 m wide. The ribs were 20 m long trapezoidal ribs with a plate thickness of 6 to 8 mm.

The plates were placed on a plane and welded in the transverse and longitudinal direction and the trough stiffeners were fitted and welded longitudinally. Plates connecting the panels and the diaphragms were welded between ribs. The 20 m long edge sections and units for the transverse diaphragm, or bulkhead, were prefabricated. The bottom and inclined sides were placed first. Each 4 m deep transverse diaphragm or bulkhead was fitted. The edge sections were installed and finally the two deck panels were placed on top, completing a 20 m long subsection. The 31 bridge girder sections for the main span were transported from the fabrication yard in Finland on the three barges in the same way as the sections for the side spans, and erected with a floating sheerleg crane, 130 m boom, starting from mid-span and proceeding towards the towers (Edwards and Westergren 1999).

In Ukraine

South Bridge over the Dnipro River

The 1992 signature span of the South Bridge over the Dnipro [Dnepr] River in Kyiv [Kiev], Ukraine is an unsymmetrical cable stayed bridge with a main span of 271 m (Korniyiv and. Fuks 1994). The main span side of the H-tower is a continuous three-span steel box girder with orthotropic steel deck. The back-span superstructure on the opposite side of the H-tower is a segmental prestressed concrete box section. Concrete construction for the shorter back span of 60 m was used as a counter-weight mass equal to the longer orthotropic main span. The bridge carries a six-lane roadway, two rail tracks and four large-diameter water pipes (Figure 10). The total live

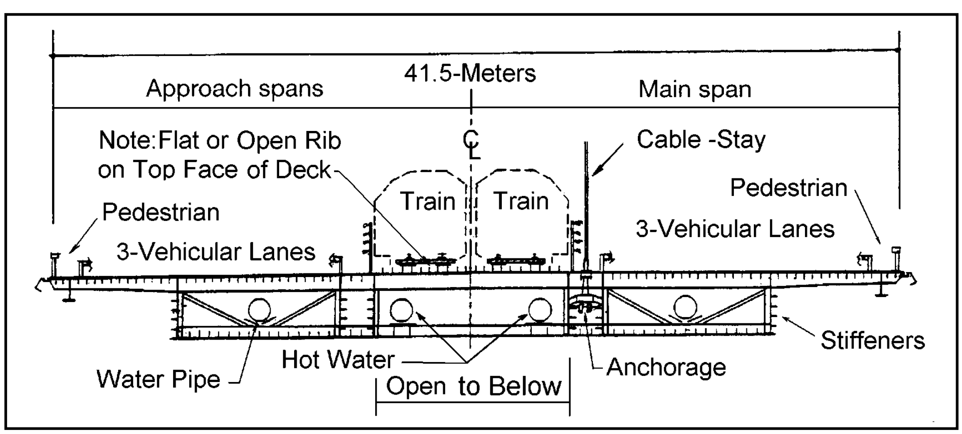

Figure 10. South Bridge (cable stayed) of Ukraine (split–section).

load is about 246 kN/m. The three-span (80.5 m + 90 m + 271 m) continuous steel box girders are made of low-alloy steel with a minimum yield strength of 390 MPa.

The bridge was divided into segments that were shop-welded. Field splices were either welded or joined by high-strength bolts. Bolting was used where automatic welding was impractical because of the short length of the weld or difficult access. The cross section of the twin two-cell box girder bridge consists of six vertical webs, the upper deck plate and the lower box flanges. The narrow cell is for the cable stayed bridge anchorage. In the central portion of the cross section that carries the two hot water supply pipes, the lower flange was omitted to preclude the undesirable effects of unequal heating inside a closed box. The bearings at the piers permit lateral displacement of the superstructure because of the 41.5 m bridge width. The orthotropic decks, bottom flanges of the boxes and the webs have open flat-bar stiffening ribs, a common feature in Ukrainian and Russian bridges. Longitudinal flat or open ribs were placed on the top face of the orthotropic deck plate under the rail tracks, thus avoiding intersections of longitudinal and transverse stiffeners.

This facilitated fabrication, at the same time precluding stress concentrations at crossing welds that would be susceptible to fatigue under dynamic train loading. Longitudinal ribs under the train tracks have a depth in excess of the design requirements, which permitted longitudinal profile adjustments of the tracks after erection of the bridge superstructure. The steel girders were pre-assembled on the bank of the south and erected by launching. The twin two-cell box girders were equipped with a launching nose and stiffened with a temporary strut system (Rosignoli1999). Single erection rollers were used at the tops of supports and had a friction factor of less than 0.015. The erection of the 271 m main span was accomplished with two false work supports providing three equal spans of about 90 m. At the H-tower of the cable stayed bridge, hinged conditions are provided by supports with limited rotational capability in the vertical and the horizontal planes. The torsional rigidity of the bridge is supplied by the two planes of cable stays, plus the stiffness of the closed box sections. Under one-sided loading of the bridge (three traffic lanes), the deck cross slope of 0.3% was measured in field tests, less than the calculated value of 0.35%. Eccentric hinged connections between the bottom flanges of the stiffening girders and the H-tower were constructed, considerably reducing the bending moments in the girders.

Conclusion

The foregoing examples illustrate a range of creative responses to the challenge of designing and constructing orthotropic steel deck bridges in cold weather regions. The versatility, economy and structural integrity of welded orthotropic design undoubtedly will continue to inspire bridge designers and structural engineers in the 21st century.

Figure Credits

Figure 1 from Ballio, G., Mazzolani, F. M. 1983, "Theory and Design of Steel Design Structures," Chapman & Hall Ltd. courtesy of Dr. Mazzolani; Figures 2, 3, & 4 courtesy of Dr. Ing. A-Aas–Jakobsen, AS Structural Engineering Consultants, Oslo, Norway; Figure 5 adapted from Aune, Petter, and Holand, Ivar (1981); Figure 6 courtesy of Mr. L. Adelaide of Profilafroid, France; Figures 8 & 9 courtesy of Claus Pedersen of Mondberg & Thorsen AS, Copenhagen, Denmark; Figures 7 & 10 courtesy of IABSE International Association of Bridge Structural Engineers.

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