The Bridge Symphony

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Summary

The Bridge Symphony is a recently developed long span bridge concept intended for spans 1000 – 3000m. The superstructure is split in 2 main girders connected by crossbeams, and carried in a longitudinal combination of a suspension bridge, a cable stayed bridge and a cantilever bridge. The towers are centric mono-towers, and the cable-stays and hangers are connected to the crossbeams on the inside of the bridge girders. Section models of the superstructure are tested in wind tunnel with favorable results. Compared to a suspension bridge with the same span, the Bridge Symphony provides better wind stability, has shorter construction time and lower cost.

Keywords: Long span hybrid bridge, dynamic behavior, wind tunnel test.

1. Briefly about the Bridge Symphony

With three different support systems in one and the same structure, the Bridge Symphony is a newly developed Norwegian bridge concept intended for extremely long spans between 1000 to 3000 meters. The name, “Bridge Symphony”, is derived from the three different bridge types composing the bridge.

The structure’s fundamental features are shown in fig.1 and 2. It is worth noting the following main properties:

- The bridge roadway is a composite of three consecutive bridge types (concrete cantilever bridge, cable-stayed bridge and suspension bridge), and is split in two parallel girders which are connected with crossbeams.
- There are two centrically placed mono-towers with a circular or rectangular hollow cross section.
- The suspension section of the bridge is supported by a centric cable, via hangers that are anchored into the crossbeams on the inner side of the bridge beams. The cross beam and the pair of hangers provide for a triangular shape which provide inherent stability in torsion.
- The bridge structure is a new development, but employing well tested components and materials.

Thus far (2001–2006), Aas-Jakobsen’s work reveals that the Bridge Symphony has considerable advantages over a conventional suspension bridge within the following areas:

- Considerably larger wind stability and lower “drag”-factor
- Reduced risk of delays due to bad weather for the tower construction as material and worker transport and escape route can be accommodated inside the tower
- Shorter construction period
- Cost reduction because of more efficient and direct load transfer
- More easily accessible for inspection and maintenance

The development of this concept is based on decades of experience with long span bridges world wide and offshore Condeep structures in the North Sea. In particular has Aas-Jakobsen's work with the Stonecutters Bridge in Hong Kong and the new Svinesund Bridge between Norway and Sweden has been influential for the further development of this cutting-edge bridge concept.

Both in Norway and other countries there is a pressing need, and strong desire, to accomplish in the near future several fiord and strait crossings which have relatively long spans. The Bridge Symphony is a new inventive concept to achieve a reliable and affordable bridge for such long spans.

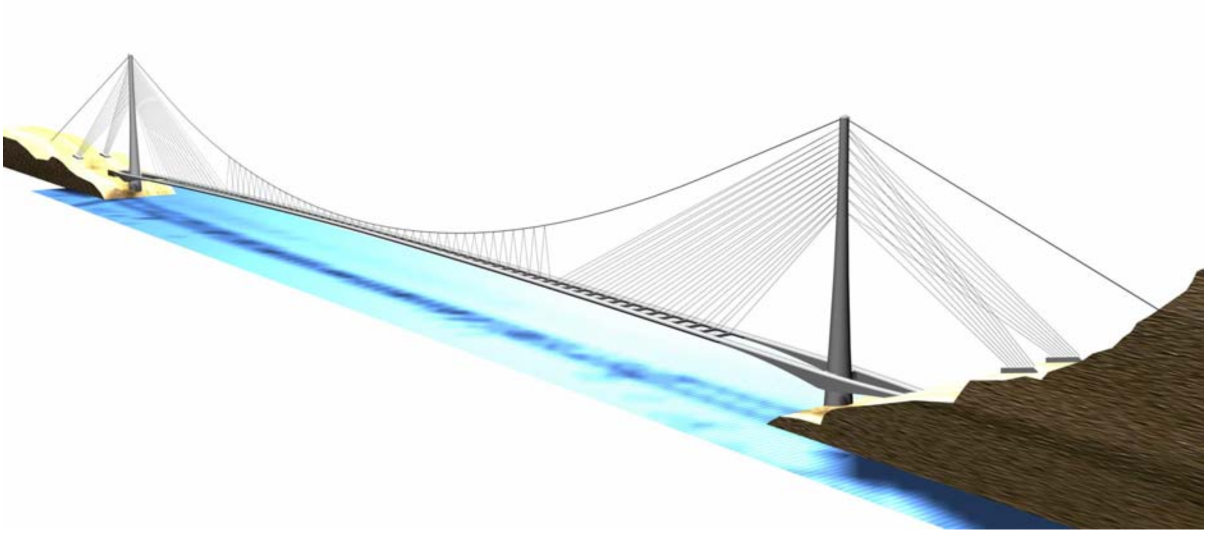

Fig. 1 A perspective picture of the Bridge Symphony (drawing by Aas-Jakobsen).

2. Technical details

2.1 Bridge deck

In order to obtain a long span wind stable structure, divided or split bridge girders are used. The girders are connected with crossbeams that are supported by hangers or stay-cables. As a result, the mid-span consists of a cantilever section closest to the mono-towers, thereafter a cable-stayed section before a transition to the middle section of the bridge, which is a suspension bridge.

The cantilever section of the bridge is concrete, and is monolithically connected to the towers. This requires that at least one expansion joint is installed in the mid-span. So far it is found to be most favorably placed between the cable-stayed and suspension sections of the bridge. Hydraulic shock absorbers are also employed to improve the bridge's dynamic behavior.

The cable-stayed section can be built with a concrete box cross section, as a composite structure with a steel trough and concrete slab, or as an orthotropic steel box. Stiffness requirements and cost assessment are important factors for determination of length and type of the cablestayed section and deck structure. Crossbeams are placed where a set of stay-cables meets the inner side of each box girder.

The suspension part of the bridge consists of two orthotropic steel boxes connected with crossbeams where a pair of hangers meets the inner side of each box.

The back spans are also constructed as a concrete cantilever, and are in equilibrium with the cantilever section in the mid-span. Depending on the topography of the bridge site, it may be feasible to continue with the cable-stayed section in the back spans.

For Norwegian conditions with 2 traffic lanes only, each bridge box girder has a width between the guard railings of no less than 6.0 meters, which permits for automobile passing on the roadway; a criterion in accordance with the new trunk road standard. The height of the bridge box girder is typically 2.5 meters. The steel boxes in the cable-stayed and suspension bridge parts have a wind nose on the outer side. The open distance between the box girders varies from just a little over the tower diameter, as they pass the mono-towers (approx. 20 meters for a span of 1350 meters), to no less than 8 meters in the mid-section of the bridge. A height of 1.5 meters for the guard railing is recommended, with circular or rectangular steel pipe as horizontal elements. An optional pedestrian and bike path can be built as a separate bridge, centrically placed on the crossbeams.

In contrast to a traditional suspension bridge, the Bridge Symphony has four properties which contribute to increased wind stability. First and foremost, the roadway is split in two sections with an opening between. Secondly, the hanging suspenders and staycables hang at an angle or slant in a plane normal to the bridge's center line, and can therefore force the bridge's main girders into another vibration pattern than that of a traditional suspension bridge. Thirdly, by having a cantilever and cable-stayed bridge section closest to the towers, a considerable increase in the bridge's stiffness is obtained, particularly if compared to a mere suspension bridge. Fourthly the transverse stiffness of the deck is important for these long spans. This can easily be obtained by widening the distance between the two girders.

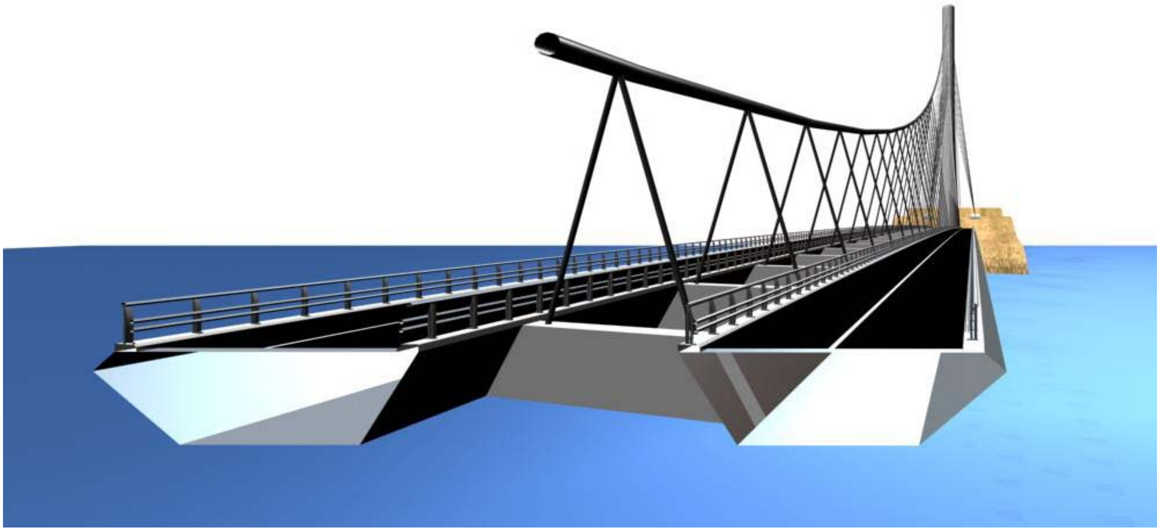

Fig. 2 A suspension bridge section at midspan (drawing by Aas-Jakobsen).

2.2 Tower and tower-saddle

Thus far, the towers are presumed to be circular with varying diameters and a typical wall thickness of 0.5 meters. For a main span of 1350 meters and a sailing clearance of 50 meters, the tower height should be approx. 200 meters, and for a main span of 2000 meters, it should be approx. 275 meters high.

The towers will be constructed in concrete, and can be built with climbing or slip forms. In principle, there is very little difference between this type of bridge tower and a column on a Condeep oilplatform in the North Sea. However, the top of the tower is given a stronger cross section in order to carry the forces of the stayed cables. This large cross section provides for inside access to the top of the tower as well as for transport of material inside the tower, by both crane and elevator, together with a stairway.

The tower foundation can be formed as a simple circular wall with footing in concrete, which is subject to compressive forces only.

Over the top of the tower the cable is placed in a saddle form, which ensures a safe transfer of forces from the cable to the top of the tower. The tower-saddle can be constructed by applying welded steel plates or machined cast steel.

In order to protect and shelter the cable over the top of the tower, it should be encased in an airtight house. The interior of the housing should be dehumidified.

2.3 Cables and hanging suspenders

The main cable is circular, and is made up of parallel wires with a diameter of 5.5 millimeters. The cable is assumed constructed by on-site spinning. The individual wires are laid together, one over the other, and coiled into a bundle. Once all the bundles are mounted, the whole main cable is worked and compressed into a circular form, thereafter a coil paste is applied and the cable is then wrapped with 3.5 millimeter heated galvanized steel wires along its whole length. The cable is then painted. This same procedure is used for the latest big suspension bridges in Norway as well as on many large international suspension bridges.

According to erection experts, the mounting of extremely long hanging cables, by way of spinning them on location, is a relatively straight forward operation. Furthermore, a mono-cable is more cost efficient than two cables half the size.

The cable is the main component of the bridge's load carrying system, and in theory it is not possible to shift or replace it once mounted. A quality protection against cable corrosion is therefore of utmost importance. The most common method for corrosion protection of this type of cable is to galvanize each individual wire, for thereafter to surface treat the finished cable with paint high in zinc content. In addition, it may be of interest to consider dehumidifying the cable.

A system for dehumidifying is based on pressing dehumidified air through the interior of the cable. This is possible because the empty space, which always remains between the circular wires in the cable, accounts for 20% of the cable's cross section, and it is through this vacant space the dehumidified air is pressed. Stipulated expenditures for this system are included in the overall cost estimates. Recently, a similar dehumidifying system for cables was subsequently mounted on the ”Høga Kusten” suspension bridge in Sweden. The cost of doing this is considerable, but is anticipated to be much less if the system is installed during the building process rather than afterwards.

For economic reasons, it is of interest to deploy the highest quality steel available on the commercial market. Thus, 1860-quality steel is used in optimized calculations of the Bridge Symphony.

It is assumed that the hangers are made of lock coil cables with galvanized wires. The same type of hanging suspenders is used on all the large suspension bridges built in Norway in recent years. Anchors for the top end of the suspenders are shaped as circular clamps, which are then bolted together around the cable. The clamps are made of two half-sections of machined cast steel.

2.4 Cable-stays

The cable-stays are of a traditional type, and consist of parallel galvanized strands that are enveloped in a plastic pipe filled with grease. The cable-stays may also be of the lock coil type. The lower anchor is fastened to the crossbeam close to a bridge girder, with access for mounting and inspection from within the crossbeam. The upper anchor is fastened to the top of the tower from within the tower wall, where there is also plenty of space for tensioning of the stay.

3. Consequences for estimated costs and building time

The mid suspensionsection of the bridge is built with orthotropic steel boxes in order to:

- Minimise the net weight of the bridge roadway, and thereby reduce the cross section and weight of the hanging cable;
- Pre-fabricate and hoist on site the finished bridge girders in large segments.

Toward the tower, a cable-stayed structure is used, which then goes over to a cantilever structure. The reasoning for this is as follows:

- It is cost efficient to carry the load directly to the tower instead of via the hanging cable since the distance to the tower is shorter, and, if in the latter case, the whole length of the hanging cable would need to be strengthened.
- A cable-stayed structure is assumed to be more cost efficient than a concrete cantilever structure with a cantilever length over approx. 100 meters, since the tower in any case must be built for the hanging cable.
- Installing the cable-stayed section can be done simultaneously with the hanging cable being spun. The bridge girders are constructed as orthotropic steel boxes or as composite boxes. A concrete cross section can also be considered.

- A concrete cantilever structure is more suitable for cantilever lengths less than approx. 100 meters. These cantilevers can be built simultaneously with the tower construction above deck level.
- Concrete cantilevers and cable-stayed sections provides greater bridge beam stiffness than a pure suspension bridge.

With a split bridge deck, the tower stands out as a single flagpole pillar. This is both a cost efficient and a safe and weather-independent solution since it can be built with slip or climbing forms, with a light weight crane mounted on the form. All transport of materials and personnel can take place inside the tower. Similar structures comparable in height are previously built for oil platforms.

Our cost analyses at the preliminary stage of the project have so far shown that the Bridge Symphony is 10-20% less expensive than a traditional suspension bridge with a span interval of 1300 to 1500 meters. A cost difference between the different bridge types will, to a certain extent, vary due to topographical conditions, number of roadways and pedestrian/bike paths. Furthermore, construction of the Bridge Symphony is estimated to take 6 to 9 months less time.

4. Tests in the wind tunnel and dynamic wind analyses

During 2004 and 2005 wind tests on a model of the Bridge Symphony were made. Tests were carried out by Svend Ole Hansen ApS (Copenhagen, Denmark) in collaboration with Professor Erik Hjorth-Hansen and Dr.Ing. Jasna B.Jakobsen at the Norwegian Technical University. The wind tunnel tests focused on the following:

- Static load coefficients
- Aerodynamic admittance functions
- Flutter derivatives
- Flutter induced vibrations
- Vortex induced vibrations

The English term “flutter” is used here for coupled oscillations (vertical displacement and torsion). The measured aerodynamic admittance functions and flutter derivatives are used for calculating the dynamic response and critical wind speed.

Fig. 3 was taken during one of the section model tests.

Fig. 3 A section model.

The tests were done on a 1.7 meter long model made to the scale of 1:50. The tests corresponded to a full scale speed of wind of up to 150 m/sec. Models of the Bridge Symphony were tested with varying distances between the two roadways, and hence tests on four different models were carried out, with 15, 20, 25 and 30 meters respectively between the centre line of the two roadways. Wind tunnel tests were also carried out on models with and without a pedestrian and bike path. Fig. 4 shows a model of a bridge segment.

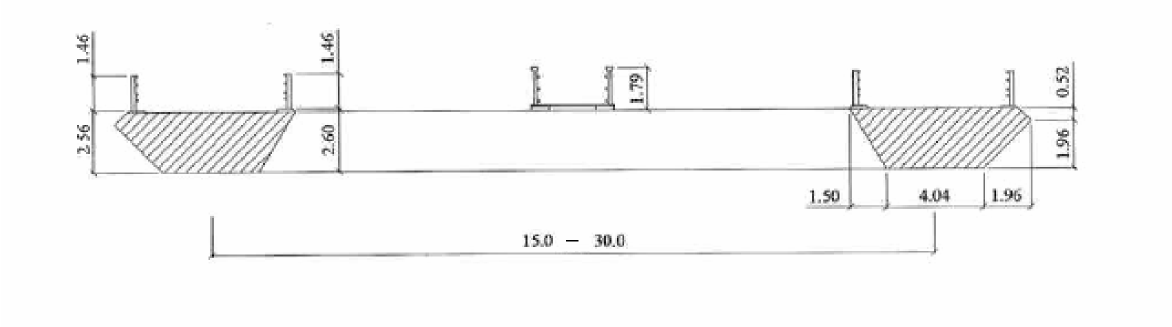

Fig. 4 Model of a bridge segment.

Wind tunnel tests were first carried out to verify the proposed bridge cross section. As it turned out, the vibrations for the original cross section were somewhat larger than expected for the bridge with the shortest distance of 15 meters between the two roadways.

Based on these results, the cross section was modified and equipped with guide vanes. This proved to be a highly aerodynamically stable structure. Consequently, two different variations were prepared, both of which in their own way reduced the response for flutter and vortex induced vibrations respectively. Tests revealed that the response was effectively reduced, and that the guide vanes are useful and cost-saving for improving the wind stability.

The two different models with guide vanes are shown in fig.5. For a bridge cross section with 15 and 20 meters between the centre lines of the two roadways, the guide vanes were placed at the base of the two bridge girders, as shown in the upper cross section in fig.5. With a cross section of 30 meters between the centerline of each roadway, the 2 meters wide guide vanes were placed on top of the cross beams, as shown in the lower cross section in fig.5.

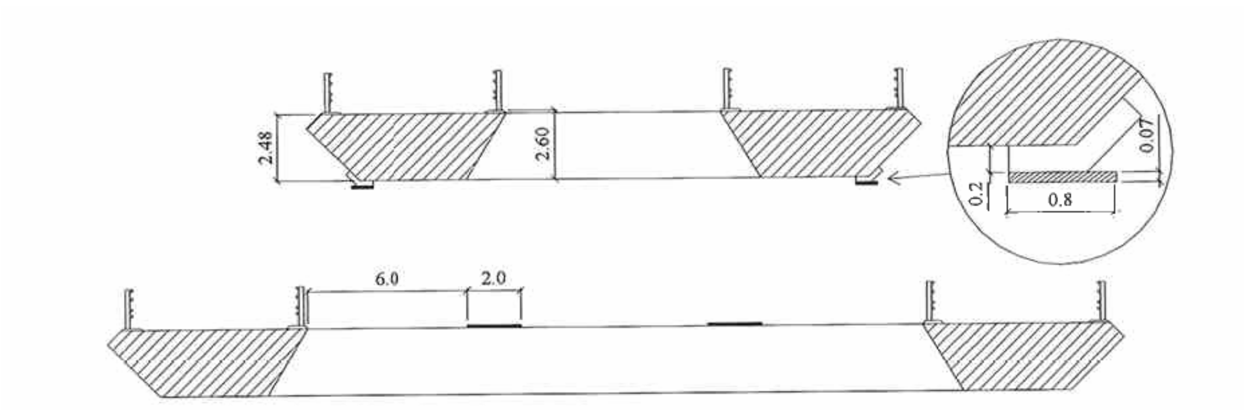

Fig. 5 Model with guide vanes.

Table 1 shows results for the critical flutter velocity at full scale for the torsion frequency n=0.237, width b=7.5 meters and with guide vanes. ‘>’ indicates that the critical flutter velocity was not found within the tested wind velocity intervals.

Distance between box girder sections	Critical flutter velocity with walking/cycle path included	Critical flutter velocity without walking/cycle path included
15 m	75 m/s	>150 m/s
20 m	126 m/s	>150 m/s
30m	>128m/s	>150 m/s

Table 1 *Results from wind tunnel tests, critical flutter velocity*.

5. Maintenance advantages

By fastening the hanging suspenders and stayed cables to the crossbeams on the inner side of the bridge girders, it is possible to carry out inspection and maintenance on the underside of the bridge roadway with the assistance of a bridge lift. On traditional suspension bridges, this is, in practice, quite difficult. In this connection it is our experience that the traditional maintenance carriage is seldom operative after the first time it has been used.

Furthermore, because each roadway is wide enough for passing of two cars in one direction, it is not necessary to close a traffic lane when the bridge lift is in use.

6. Esthetics

Architect Rolf H. Gulbrandsen was engaged to give an architectural evaluation of the Hålogaland Bridge (main span 1350m) designed as a Bridge Symphony.

The concept was positively received, and additional feedback from Gulbrandsen is indicated below:

”There is little doubt that the bridge concept’s main idea can be implemented in a positive innovation. Thus far, it would seem that the project’s combination of structures could take on a satisfactory architectural expression.

A split roadway past the central tower must be closely studied in relation to the roadway’s further alignment. Otherwise, it is precisely the split roadway with the towers in the center and just one hanging cable that are viewed to be the project’s most positive essence.”

7. Acknowledgement

A major part of the design and development of the Bridge Symphony is done by senior bridge engineer Elljarn A. Jordet, and most of the analysis and wind dynamics calculations are performed by senior structural engineer dr.tecn. Knut Aas-Jakobsen.