Application of high strength steel in super long span modern suspension bridge design

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ABSTRACT: COWI recently prepared design for three long span suspension bridges: Hálogaland Bridge in Norway (Basic Design, 1,345m main span), Messina Bridge (Tender Design, 3,300m main span) and Yemen-Djibouti Bridge (Sketch Design, multi span suspension bridge with four spans of 2,700m each. Huge tonnages of steel are required for cables, bridge decks and pylons. Innovative solutions were developed for all three bridges to overcome the challenges of spanning up to 3,300m for combined road and rail traffic and designing bridges with lifetimes up to 200 years. Profound water depths of up to approx. 300m require long spans. Application of high strength steel makes it possible to create economical designs. Dead load plays an important role in the design of huge suspension bridges and it is therefore of utmost importance to apply the optimum steel grade in order to minimize weight and reduce the construction costs. As an example 1 ton saved in the bridge deck for Messina Bridge results in 1.2 ton less cable steel and related savings in pylons and anchorages. The paper focuses on bridge concepts, the utilisation of S420 and S460 in the design of bridge decks and pylons, application of cable wire strengths up to 1,860MPa and advanced corrosion protection systems for cables.

1 INTRODUCTION

COWI recently prepared design for three long span suspension bridges:
- Hálogaland Bridge, Norway: Basic Design, 2007, 1,345m single span suspension bridge with mono box steel girder as bridge deck (road traffic), A-shaped pylons and inclined cable planes
- Messina Bridge: Tender Design, 2005, 3,300m main span suspension bridge with steel pylons and triple steel box concept for the bridge deck (road and rail traffic)
- Yemen-Djibouti Bridge: Sketch Design, 2008, multi span suspension bridge of 12.7km with four spans of 2,700m each, continuous cables, concrete pylons and triple steel box concept for the bridge deck (road and rail traffic)

Dissing+Weitling acted as bridge architect for COWI for all projects.

Figure 1. Renderings of Hálogaland Bridge (left), Messina Bridge (centre) and Yemen-Djibouti Bridge (right), prepared by Dissing+Weitling A/S.
The bridges will span straits with profound water depths - up to 300m. This is one reason for long span solutions. Another reason is navigational clearance requirements for international shipping traffic.

The projects were developed based on the experience from:

- **Gibraltar Bridge**: Sketch Design, multi span suspension bridge, 3,550-5,000m spans, main design for road traffic with alternative design for combined road + rail traffic
- **Great Belt East Bridge**: Detailed Design, suspension bridge, 1,624m main span, road traffic
- **Chacao Bridge**: Tender Design, multi span suspension bridge, 1,055-1,180m spans, road traffic
- **Stonecutters Bridge**: Detailed Design, cable stayed bridge, 1,018m main span, road traffic
- **Øresund Bridge**: Detailed Design, cable stayed bridge, 490m main span, road + rail traffic.

## 2 BACKGROUND

Hålogaland Bridge is located at Narvik in northern Norway, crossing "Rombaksfjorden" with water depths up to 350 m. The bridge is part of a new alignment of the E6 highway between Narvik and Bjerkvik which when completed will shorten the existing E6 by 17 km, see Figure 2. The COWI Team prepared Basic Design and construction cost estimates for a suspension bridge alternative on behalf of the Norwegian Public Roads Administration, Region North. The COWI Team consists of:

- COWI A/S (project management, global and aerodynamic analyses, cable system, steel box girder and approach viaducts)
- Dissing+Weitling A/S (bridge architect)
- Johs. Holt AS (pylons incl. foundations)
- Norwegian Geotechnical Institute (expert advice on rock cable anchorages and foundations).

Figure 2. Location of Hålogaland Bridge (left, prepared by Hålogalandsbrua AS), Messina Bridge (centre) and Yemen-Djibouti Bridge (right).

Messina Bridge connects the coasts of Sicily and Calabria in southern Italy and when built will replace today's ferry crossings, see Figure 2. The bridge has a world record breaking 3,300m main span surpassing Akashi-Kaikyo Bridge in Japan (main span of 1,991m) by 65%. The design life of the bridge is 200 years. COWI carried out pre-bid investigations in 2003-2004 and Tender Design in 2004-2005 on behalf of ATI Impregilo - a consortium led by the Italian Contractor Impregilo SpA. The Tender Design comprised the following activities:

- Structural design of all structures incl. global FE-modelling and foundation models
- Design and/or technical specifications for secondary structures and systems - i.e. wind screens, service lanes, access facilities, pavement, rails, bearings, expansion joints, buffers etc.
- Basic studies - i.e. seismic, aerodynamic, risk, runability, safety and comfort analyses etc.
- Operation & Maintenance incl. Life Cycle Costs
- Technological systems - i.e. management & control system, electrical and mechanical installations, structural monitoring system, anti-sabotage facilities etc.

Yemen-Djibouti Bridge comprises a fixed link between Yemen and Djibouti across the Bab El Mandeb Strait which connects the Red Sea to the Indian Ocean via the Gulf of Aden, see Figure 2. The island of Perim divides the strait into the Small Strait approx. 3.5km wide (water depth approx. 20m) and the Large Strait approx. 21.5km wide (water depth up to approx. 300m). COWI prepared Sketch Design on behalf of Middle East Development LLC. Yemen-Djibouti Bridge is part of a huge development project with a total budget of approx. US$ 200 billion (the bridge costs are approx. US$ 21.5 billion). The bridge will link two new cities for totally more than 7 million people.
thereby creating a new region called Al Noor City (City of Light) and providing a gate to Africa from the Arabian Peninsula. The bigger city is located in Yemen and is envisaged to have 4.5 million inhabitants. The other city is located in Djibouti and is planned for 2.5 million inhabitants. The time horizon for the project is 15-20 years. The Sketch Design is considered as the first step towards Pre-feasibility and Feasibility Studies at later project stages. The objective is to prepare a desk study for a bridge solution along one selected alignment based solely on readily available information. This means that surveys and site investigations has not been carried out yet but will be required tasks for inclusion in the next project stages. The Sketch Design comprised the following activities:
- Establish functional requirements
- Collect and study relevant information
- Prepare preliminary Design Manual
- Develop Sketch Design
- Estimate construction costs
- Estimate construction schedule.

3 BRIDGE CONCEPTS

Hålogaland Bridge is arranged as a single span suspension bridge with A-shaped concrete pylons, inclined cable planes and a closed steel box girder as bridge deck in the main span, see Figure 3. Basic Design and construction cost estimates were prepared for two solutions. Solution 1 is arranged with the pylons founded on shore directly on rock resulting in a 1,345 m main span. Solution 2 is with 1,120 m main span and the pylons founded on caissons in the sea at water depth of approx. 25 m. Solution 2 results in a cost saving of approx. NOK 100 M mainly due to reduction in length of a tunnel connecting to the bridge.

Figure 3. Hålogaland Bridge, layout of solution 1.

Messina Bridge is arranged as a single span suspension bridge with a main span of 3,300m. The suspended parts of the side spans are very short due to local topography. Both pylons are located onshore. The pylon locations and the length of the main span is fixed by the bridge owner, Stretto di Messina SpA, see Figure 4. The vertical clearance is 65m at mean water level.

Figure 4. Messina Bridge, bridge layout.

Yemen-Djibouti Bridge consists of 3 parts: 5.95km long Djiboutian Viaduct, 12.7km long suspension bridge and 10.3km long Yemeni Viaduct, see Figure 5 top. The total length of the bridge is 28.95km. A considerable part of the crossing of the Large Strait will necessarily consist of large suspension bridge spans due to the extreme water depth and the navigation clearance required for international shipping traffic. The Sketch Design is thus based on a multi-span suspension bridge of 12.7km with four spans of 2,700m each, see Figure 5 bottom. The span length is determined by the
width of today's navigation channels whereas the vertical clearance is determined by ships coming from Suez Canal as it is assumed that most ships sailing from Suez Canal will continue through Bab El Mandeb Strait. Therefore Yemen-Djibouti Bridge shall as a minimum adopt the vertical clearance of 70m at mean water level of Mubarak Peace Bridge crossing the Suez Canal. In order to allow for future development of the ship traffic a vertical clearance of 73m is adopted for the two main navigation corridors. The most economical solution is to arrange the bridge as a multi span suspension bridge instead of a row of classical three span suspension bridges. This is to avoid the costly anchor blocks on extremely deep water. Consequently, the cables are continuous from one anchor block to the other. Both anchorages are gravity based structures in about 50-60m deep water. Figure 5. Layout of Yemen-Djibouti Bridge, fixed link (top), suspension bridge (bottom).

Figures

4 APPLICATION OF HIGH STRENGTH STEEL IN CABLES

General data for the cables of the three bridges are given in Table 1. The cables of Hålogaland Bridge and Yemen-Djibouti Bridge are arranged as single cables and thereby two cables are required for each of the bridges. The cables of Messina Bridge are twin cables 1.75 m apart. A total of four cables are required for the bridge.

Table 1. General data for the cables of the three suspension bridges

<table>
<thead>
<tr>
<th>Unit</th>
<th>Hålogaland Bridge (solution 1)</th>
<th>Messina Bridge</th>
<th>Yemen-Djibouti Bridge (suspension bridge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span (m)</td>
<td>1,345</td>
<td>3,300</td>
<td>2,700</td>
</tr>
<tr>
<td>Span to sag ratio</td>
<td>10</td>
<td>11</td>
<td>8.5</td>
</tr>
<tr>
<td>Cable wire strength (MPa)</td>
<td>1,770</td>
<td>1,860</td>
<td>1,860</td>
</tr>
<tr>
<td>Cable area (m²)</td>
<td>0.17</td>
<td>2 x 0.92</td>
<td>0.87</td>
</tr>
<tr>
<td>Cable diameter (m)</td>
<td>0.52</td>
<td>2 x 1.20</td>
<td>1.17</td>
</tr>
<tr>
<td>Cable length (m)</td>
<td>2,055</td>
<td>5,290</td>
<td>13,350</td>
</tr>
<tr>
<td>Cable steel (t)</td>
<td>5,350</td>
<td>153,000</td>
<td>185,000</td>
</tr>
</tbody>
</table>

A significant part of the force in the cables of long span suspension bridges arises from dead load. The distribution of the unfactored tension in the cables for the three bridges are given in Table 2 and it appears that for the Messina Bridge 47% of the tension arises from the dead load of the cables.

Table 2. Distribution in percentage of unfactored tension in the cables of the three suspension bridges

<table>
<thead>
<tr>
<th>Distribution of unfactored tension in the cables</th>
<th>Hålogaland Bridge (solution 1)</th>
<th>Messina Bridge</th>
<th>Yemen-Djibouti Bridge (suspension bridge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load, cables</td>
<td>20%</td>
<td>47%</td>
<td>32%</td>
</tr>
<tr>
<td>Dead load, steel deck</td>
<td>42%</td>
<td>22%</td>
<td>37%</td>
</tr>
<tr>
<td>Dead load, pavement</td>
<td>19%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Dead load, equipment</td>
<td>4%</td>
<td>7%</td>
<td>6%</td>
</tr>
<tr>
<td>Dead load, total</td>
<td>85%</td>
<td>77%</td>
<td>77%</td>
</tr>
<tr>
<td>Variable loads</td>
<td>15%</td>
<td>23%</td>
<td>23%</td>
</tr>
</tbody>
</table>

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It is therefore obvious that significant cost savings can be obtained in cables and cable anchorages together with related savings in pylons and construction time by adopting the highest possible breaking strength of the main cable wires. This reduces cable forces due to dead load and cable quantities. It is nowadays possible to use wires with minimum breaking strength of 1,770, 1,860 and 1,960 MPa. The availability of 1,960 MPa wires is limited, but the 1,860 MPa wires are readily available. A case example from Messina Bridge illustrates this. The Tender Design was initially based on 1,770 MPa wires, but at a certain stage it was concluded that it would be beneficial to base the design on 1,860 MPa wires considering supply, quantities, construction time and cost. Table 3 compares the results for Messina Bridge applying either 1,770, 1,860 or 1,960 MPa wires as reference. The saving in cable quantity is significant. It is noted that higher strength leads to a slightly more flexible structure and smaller cable diameter resulting in smaller wind load on the bridge structure.

Table 3. General data for the cables of the three suspension bridges

<table>
<thead>
<tr>
<th>Cable wire strength</th>
<th>Area</th>
<th>∆-quantity</th>
<th>Deflection</th>
<th>Cable diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,770 MPa</td>
<td>110%</td>
<td>+15,300 t</td>
<td>94%</td>
<td>1.26 m</td>
</tr>
<tr>
<td>1,860 MPa</td>
<td>100%</td>
<td>-</td>
<td>100%</td>
<td>1.20 m</td>
</tr>
<tr>
<td>1,960 MPa</td>
<td>91%</td>
<td>-13,800 t</td>
<td>106%</td>
<td>1.14 m</td>
</tr>
</tbody>
</table>

5 APPLICATION OF HIGH STRENGTH STEEL IN BRIDGE DECKS

The suspended bridge decks for Messina Bridge is formed by three independent longitudinal steel box girders, two for the roadway and the central one for the railway, see Figure 6. The boxes are connected by cross girders at 30 m spacing. Thereby the triple box concept for a bridge deck will be adopted for the first time. The bridge deck for Yemen-Djibouti Bridge is similar. The bridge deck for Hålogaland Bridge is arranged as a closed steel box girder with a depth of 3.0 m.

Figure 6. Messina Bridge, layout of the bridge deck.

It is seen from Table 3 that a significant part of the unfactored tension in the cables arises from the dead load of the bridge deck. For the Messina Bridge 22% of the tension arises from the dead load of the bridge deck. It is therefore obvious that the weight of the suspended deck itself is one of the driving factors of the project cost as lower weight will lead to savings in cables, pylons, foundations and anchorages.

The weight of the suspended deck for the three bridges is given in Table 4. It appears that the weight per m² is of the same magnitude for all bridges. It is also seen that the weight of the suspended deck of long span suspension bridges is significant and therefore it is important to optimise the design of the deck to achieve minimal weight. This is illustrated by a case example from Messina Bridge. 1.0 t/m saved in the bridge deck results not only in a saving in the suspended deck but also in a saving of 4,350 t cable steel and related savings in pylons and anchorages. In conclusion for each ton of steel saved in the suspended deck 1.2 t is saved in the cables.
Table 4. Weight of suspended deck for the three suspension bridges

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Hålogaland Bridge (solution 1)</th>
<th>Messina Bridge</th>
<th>Yemen-Djibouti Bridge (suspension bridge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel, suspended deck</td>
<td>t</td>
<td>7,450</td>
<td>62,500</td>
<td>245,000</td>
</tr>
<tr>
<td>Length, suspended deck</td>
<td>m</td>
<td>1,345</td>
<td>3,635.5</td>
<td>12,700</td>
</tr>
<tr>
<td>Effective width, suspended deck</td>
<td>m</td>
<td>13.0</td>
<td>34.2</td>
<td>35.2</td>
</tr>
<tr>
<td>Weight, suspended deck</td>
<td>t/m</td>
<td>5.5</td>
<td>17.2</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>kg/m²</td>
<td>426</td>
<td>503</td>
<td>548</td>
</tr>
</tbody>
</table>

In general S355 in accordance with EN 10025 is applied but higher strength steel like S420 and S460 is applied in areas where they can be utilized to minimize the weight. A case example from Messina Bridge shows the optimized distribution of steel grades:

- Roadway girders: starting from mid span S355 is applied as longitudinal steel for the first 630 m, S420 for the next 360 m and S460 for the remaining part. S355 is applied for diaphragms.
- Railway girder: starting from mid span S355 is applied as longitudinal steel for the first 990 m, S420 for the next 510 m and S460 for the remaining part. S355 is applied for diaphragms.
- Cross girders: S460 is applied for all cross girders. S355 is applied for diaphragms.

The distribution expressed in percentages of the steel among the various steel grades and the structural elements is shown in Table 5. Steel grade S460 is used for 57%, S420 for 13% and S355 for the remaining 30% of the suspended deck. The consequences of not applying high strength steel would be that the weight of the suspended deck would increase by approx. 3.3 t/m resulting in increased steel quantities of approx. 12,000 t in the suspended deck and 14,000 t in the cables. Quantities would also go up in pylons, anchorages and foundations. The saving in suspended deck and cables alone might be more than 100 million EUR assuming unit costs of 6,000 EUR/t for steel and 4,000 EUR/t for cable wire.

Table 5. Messina Bridge, Distribution of the steel for the suspended deck in ton and expressed in percentages

<table>
<thead>
<tr>
<th></th>
<th>Road girders</th>
<th>Rail girder</th>
<th>Cross girders</th>
<th>Total</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355 (t)</td>
<td>11,500</td>
<td>5,600</td>
<td>1,800</td>
<td>18,900</td>
<td>30%</td>
</tr>
<tr>
<td>S420 (t)</td>
<td>5,800</td>
<td>2,500</td>
<td>0</td>
<td>8,300</td>
<td>13%</td>
</tr>
<tr>
<td>S460 (t)</td>
<td>12,200</td>
<td>2,600</td>
<td>20,500</td>
<td>35,300</td>
<td>57%</td>
</tr>
<tr>
<td>Total (t)</td>
<td>29,500</td>
<td>10,700</td>
<td>22,300</td>
<td>62,500</td>
<td></td>
</tr>
<tr>
<td>Percentage</td>
<td>47%</td>
<td>17%</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 APPLICATION OF HIGH STRENGTH STEEL IN PYLONS OF MESSINA BRIDGE

![Messina Bridge - Sicilia Tower. Maximum compression stresses in Tower leg](image)

Figure 7. Messina Bridge, layout of the pylons.
The pylons of Messina Bridge are frame structures with slightly inclined legs (inclination of approx. 2°) and three connecting cross beams, see Figure 7. The pylon top level is at 382.6m. Steel is preferred as material due to seismic load and construction programme. In general S460 in accordance with EN 10025 is applied and S355 is only applied in elements where the higher strength of S460 cannot be fully utilised. This is typically in horizontal cross frames and diaphragms. It is an added benefit that S460 ensures as low as possible mass of the pylon legs. The steel quantity is 97,000t in total for the two pylons split into 88,500t S460 and 8,500t S355. The overall cross section dimensions of the pylon legs are 20m x 12m along respectively transverse to the bridge axis. These dimensions ensure sufficient capacity for the governing load combination which is ULS seismic with the earthquake primarily acting in the longitudinal direction of the bridge using reasonable plate thicknesses in the order of 30-85mm, see Figure 7. The legs are designed such that the full yield strength of the steel is utilized. It is possible to design the pylon with three cross beams only because transverse wind and transverse earthquake do not govern the design of the pylon legs. The plate thicknesses are in the order of 20-25mm.

7 CORROSION PROTECTION SYSTEMS FOR CABLES

7.1 Introduction

Corrosion of cables on suspension bridges is a major problem on a worldwide basis. The cable wires are traditionally covered by a multi-barrier system composed of galvanizing of individual cable wires, zinc paste on the bundle of wires, galvanized wrapping wire and paint on the surface. Corrosion is therefore hidden and often progresses to a very serious level before it is detected. A new and better method has therefore been developed in recent years; dehumidification by dry air flow in addition to galvanizing of the cable wires. This method prevents corrosion from occurring by eliminating water/moisture in the cables which is the source of the corrosion problem. A dehumidification system blows dry air through the cables and keeps the atmosphere in the cables so dry that corrosion can not occur. Today design lifetime is in some cases as much as 200 years and dehumidification systems are able to fulfil such requirements. It is also necessary to consider Life Cycle Costs in new design as well as rehabilitation by developing and applying solutions with the lowest present net value over the entire lifetime of the bridge, including the construction cost, as well as operation, maintenance, repair and replacement costs.

7.2 Corrosion protection system for suspension bridge cables based on dehumidification

The system has been under development for about 10 years. A properly designed dehumidification system provides complete corrosion protection of the cables, as they are enclosed in an atmosphere with the relative humidity kept below 60%, such that corrosion can not occur. Furthermore, the system provides an overpressure in the cables, which prevents water/moisture from entering the cables through any small leaks that may occur in the sealing. Leakage is one way only, i.e. dry air can leak out, but water can not leak in. The design criteria take into account a certain leakage, so the necessary pressure is assured. The effectiveness is proven on bridges in Denmark, France and Japan. The development of dehumidification systems for suspension bridge cables is a natural extension of application of similar systems in steel box girders and as such it is based on considerable experience. A dehumidification system for cables is composed of three major components:

− A sealing system for the cables, including cable bands, saddles and other components
− A dehumidification system capable of producing and blowing dry air through the cables
− A control and monitoring system.

These components are designed as an integrated system to suit the individual bridge and fulfill the specific requirements. They are described below.

Extensive research, development and workshop as well as on-site testing has been carried out to determine the best sealing system which for the cable sections from band to band has proven to be application of an elastomeric wrap under tension with a 50% overlap and a total thickness of 2.2 mm, see Figure 8. The wrap is heated with a heating blanket which completely bonds the two layers and shrinks the wrap slightly giving an even tighter fit. Special details have been developed for sealing
of transition to cable bands, cable bands, saddles, injection and exhaust collars which generally are based on a double barrier system with a combination of sealer strips and adhesive caulk.

The dehumidification system produces dry air and blows it through sections of the cables. The system assures overpressure inside the sealed cable system and is made up of the following main components: dehumidification plants, injection points and exhaust points. Injection points are established by either modifying existing bridge components, such as the saddles or by designing purpose suited injection collars. Exhaust points are established in the same manner, see Figure 8.

The control and monitoring system comprises instrumentation at the dehumidification plants, in the buffer tanks and at injection and exhaust points. These instruments and plants are connected to local PLCs (Programmable Logical Computer), which in turn are connected to a central computer, which stores all data. From the central computer it is possible to adjust the system and to monitor key data such as system functionality, relative humidity, temperature, flow and pressure.

7.3 Case example: corrosion protection of the cables on Messina Bridge

The bridge authority Stretto di Messina SpA required in the tender project dehumidification of the cables be analyzed with regards to feasibility and Life Cycle Cost and compared with a traditional corrosion protection system. Dehumidification was to be applied if found advantageous. Based on experience from the dehumidification systems on other bridges, a dehumidification system for the main cables was developed. Dehumidification plants are placed in buffer tanks in the top of both pylons and at several positions in the bridge deck and in the anchorages. Dry air from the buffer tanks is injected in the main cables and flows to exhaust points. The results of the Life Cycle Cost Analysis indicate that the construction cost for a dehumidification system is 77% less and that the net present value of operation and maintenance over the first 60 years is 71% less than a traditional system. There are also substantial indirect savings in construction costs due to lighter cables.

7 CONCLUSION

This paper gives background information and technical descriptions of the bridge concepts of Hålogaland Bridge, Messina Bridge and Yemen-Djibouti Bridge. Significant cost savings can be obtained in cables and cable anchorages together with related savings in pylons and construction time by adopting the highest possible breaking strength of the main cable wires. Also reduction of the weight of the suspended deck itself by applying higher strength steel like S420 and S460 in areas where they can be utilized will lead to savings in cables, pylons, foundations and anchorages. Finally it is described how dehumidification of the cables is an efficient way to obtain a design life time of the cables of 200 years.