Bridge engineering
Major bridges
COWI, founded in 1930, is a privately owned company and completely independent of any manufacturer, supplier or contractor. The COWI Foundation is the majority shareholder and supports research and development in the various fields of consultancy activities. The head-office is located in Lyngby, a suburb about 12 km north of Denmark’s capital Copenhagen.

COWI is a leading northern European consulting group. We provide state-of-the-art services within the fields of engineering, environmental science and economics with due consideration for the environment and society. COWI is a leader within its fields because COWI’s 3,500 employees are leaders within theirs.

COWI’s staff includes engineers, planners, sociologists, biologists, agronomists, economists and other academic specialists. The net capital and annual turnover are at present EUR 79 and 376 million, respectively. More than 50% of the turnover comes from international projects.

The skills represented in the COWI Group are complementary to a very large extent, and hence we can create synergy between the versatile bouquet of disciplines required in complex projects and offer total solutions to our clients considering all constraints and options in a balanced way.

**Transportation**

COWI has more than 75 years of experience in transportation covering all phases of infrastructure projects from initial planning and feasibility studies to maintenance management and training. Roads, railways and airports with more than 3000 bridges of all types and sizes have been constructed according to COWI’s designs.

**Bridge engineering**

COWI is an international market leader in bridge engineering. Highly professional staff with broad international experience have reached this position through a continuous commitment to work of the highest professional standards and a constant search for efficient and innovative solutions.

COWI is proud to present its capabilities and achievements in bridge engineering. We have endeavoured to present COWI’s comprehensive services within bridge engineering in this brochure. Please, do not hesitate to contact us for further information.
Bridge engineering

Working with bridges
Since COWI was founded bridge design has been a core activity for COWI. We have been responsible for preliminary studies, detailed design and supervision of the majority of the Danish bridges across waterways. Among these are the world-class suspension bridge, the East Bridge, across the Great Belt with a free span of 1624 m, and the combined rail- and roadway cable-stayed bridge for the Øresund link between Denmark and Sweden with a main span of 490 m.

Bridges
COWI has been involved in bridge projects worldwide and has worked with all types of bridges as presented in the following pages.

Services
COWI’s services cover the whole project life cycle from the early ideas to the operation phase and rehabilitation or decommissioning. COWI works for public clients, concessionaires and contractors (BOT and design-build projects). COWI advocates a close dialogue with the contractors in order to optimize the design and construction. This knowledge is then reused, when we design for bridge owners.

Expertise
We are actively participating in research and development of materials, new technology and methods of analysis in order to develop our core competencies. The state-of-the-art knowledge thus acquired is used for developing innovative concepts in design such as corrosion protection of steel girders by dehumidified air and vibration control with tuned mass dampers. Our in-house integrated bridge design and analysis system, IBDAS, which is based on 3D parametric modelling, enables COWI to make state-of-the-art structural analyses and documentation.

Quality management
COWI’s bridge division is ISO 9001 certified. All design activities in COWI are performed according to a project quality plan tailored to meet the special project requirements.

Market areas
COWI is an international market leader in the design of major bridges, and we provide our services from offices in Denmark, Norway, the Gulf (Oman, Qatar, Bahrain, Abu Dhabi), East-EU (Poland, Hungary), Africa (Uganda, Tanzania), Korea, China, Canada (Buckland & Taylor Ltd) and USA (Ben C. Gerwick Inc and Ocean and Coastal Consultants Inc).

Services
• Project implementation
• Feasibility studies
• Design management
• Design
• Design check and consulting
• Construction engineering
• Construction management
• Site supervision
• Operation and management
• Re-evaluation and rehabilitation
• Decommissioning

Expertise
• IBDAS – integrated design
• Numerical analyses
• Wind engineering
• Cable-stay damping and tuned mass dampers
• Operational risk management
• Construction risk management
• Ship collision and ship impact protection
• Structural health monitoring
• Dehumidification
• Scour protection
• Construction materials
• Service life design
COWI is recognized worldwide for its state-of-the-art knowledge on suspension bridges. This knowledge has been acquired through our involvement in numerous suspension bridge projects.

New concepts
Closed box steel bridge girders, aerodynamically shaped, were introduced by COWI in the New Little Belt Bridge in Denmark at the same time as in the Severn Bridge in UK.

An innovative approach with dehumidification of the air inside the closed box girder was also introduced to avoid corrosion of the interior surfaces. This approach has later been developed for dehumidification of main suspension cables.

COWI has designed maximum expansion lengths in bridge girders to reduce maintenance and hydraulic buffers to limit bridge girder expansions.

Wind engineering
COWI introduced tuned mass dampers and application to suppress vortex induced vibrations on cable-stayed and suspension bridges.

Extreme bridge spans
Twin deck and closed elliptical bridge girder shapes have been investigated for extreme suspension spans in the range from 3,500 to 5,000 m for a road bridge crossing of the Strait of Gibraltar between Spain and Morocco. Bridge piers and construction methods for foundation at water depths of 300 to 500 m were developed utilizing technologies and concepts from deep water gravity platforms and steel jackets from the off-shore oil industry. Also a combined road and railway tender design for the 3,300 m Messina bridge has been carried out here as a triple girder deck with rail on the centre girder.

Rehabilitation design
A complete replacement design of main cables and hangers of the Aquitaine Bridge in France has been made, enabling a widening from 5 to 6 lanes. Temporary ancillary cables supported the structure during construction which was made with full traffic on the bridge.

References
- Messina Bridge, Italy
- Great Belt Bridge, Denmark
- Hålogaland, Norway
- Chacao Bridge, Chile
- High Coast Bridge, Sweden
- Aquitaine Bridge, France
- Viaduc du Chavannon, France
- Ålvsborg Bridge, Sweden
- YongJong Bridge, Korea
- Trekantsambandet, Norway
- Gibraltar Strait Crossing, Spain – Morocco
- New Little Belt Bridge, Denmark
- 2nd Bosporus, Turkey
- Hardanger Bridge, Norway

![World’s longest suspension bridge spans](Image)

Aquitaine Bridge, France

New Little Belt Bridge, Denmark
Great Belt Link, East Bridge, Denmark

The high-level motorway bridge is one of the three major components in the EUR 4 billion Great Belt Link. The East Bridge is the landmark and spans the international navigation route between the Baltic Sea and the North Sea and allows a clearance of 65 m below the bridge girder. The bridge carries a dual lane motorway with emergency lanes.

With a main span of 1,624 m the East Bridge has the second longest suspended span in the world. The side spans are 535 m each and the approach bridges are 2,544 m and 1,552 m long, respectively. The substructures including pylons, are constructed of concrete and the superstructure is of steel.

Superstructure
The superstructure is an aerodynamically shaped fully welded closed box girder and continuous over the full length of 2,694 m between the two anchor blocks. The traditional expansion joints at the tower positions are thus avoided. In addition, hydraulic buffers between the anchor blocks and the girder are installed to restrain longitudinal short-term movements. Compared to a traditional system with joints at the pylons, the continuous system in combination with the hydraulic buffers improves the overall stiffness and stability of the bridge and leads to low maintenance costs.

The box girder is suitable for rationalised repetitive fabrication. The interior surfaces, which comprise about 80 percent of the total steel surface, are unpainted and are protected by dehumidification of the inside air volume.

Cables
The length of the main cables is approximately 3,000 m with an outer diameter of 0.82 m. The cables were installed by aerial spinning.

Pylons
Rising 254 m above sea level, the pylon has slightly tapered legs with a rectangular, hollow cross-section. The lower part around the water line is designed as a monolithic structure with heavily reinforced 1.2 m thick walls to resist impact loads of 670 MN from a 250,000 DWT tanker.

The pylons are supported by large foundation caissons placed on a gravel bed at a water depth of approximately 20 m. The cellular 78 x 35 m caissons, 20 m high and weighing 30,000 tonnes, were cast in a dry dock and towed about 30 nautical miles to the bridge site.

Anchor blocks
Located at a water depth of approximately 10 m, the anchor blocks shall resist cable forces of 600 MN. Excavation to 25 m below sea level was necessary to construct a wedge-shaped foundation base suitable for large horizontal loading. Each anchor block caisson covers 6,100 m² and weighed 50,000 tonnes in the transportation stage from the dry dock.

Services
- Conceptual design
- Tender design
- Tender evaluation assistance
- Detailed design
- General supervision during construction
- Inspection and maintenance of steel structures, equipment and mechanical installations
- Implementation of IT management system
- Specialist studies, incl. ship collision

Project period
1986 – 1998
O&M superstructure ongoing

Parties
Client: A/S Storebæltsforbindelsen (Great Belt A.S.)
Designer: CBR Joint Venture with COWI as leading partner.

Photo: Per Brogaard

Photo: Mogens Carrebye
Messina Strait Bridge, Italy

The Messina Strait Suspension Bridge will connect the coasts of Sicily and Calabria in southern Italy and it will carry a four lane highway with emergency lanes and a dual railway line. The bridge will be spectacular due to the world-record breaking 3,300 m main span which is 65 % longer than the present longest suspension bridge and twice the main span of the Great Belt East Bridge. The design life of the bridge is 200 years which is twice the design life normally applied for major suspension bridges.

Suspended deck
The suspended deck is arranged with the cross-girders spaced at 30 m as the main elements, whereas the two roadway girders and the central railway girder are taken as secondary elements spanning between the cross-girders. Thereby the Messina Strait Bridge will be the first bridge in the world to adopt the triple box concept for the suspended deck. The deck is continuous from expansion joint to expansion joint – the total length is 3,666 m. The navigation clearance at mid-span is 65 m.

Cables
The main cables consist of twin cables spaced at 1.75 m – i.e. a total of four cables with a diameter of 1.2 m are required for the bridge. The sag to span ratio of the cables is fixed to 1:11. The length of the main cables is approx. 5,300 m and the distance between the main cables is 52 m.

Towers
The towers are designed using S460 steel and they are arranged as frame structures with slightly inclined legs (inclination of approx. 2°) and three connecting cross-beams. The overall dimension of the tower leg cross-section is 20 x 12 m, and the tower top level is at 382.6 m.

The tower legs are founded inside circular diaphragm walls on two circular foundations which are connected by a concrete box tie.

Anchor blocks
On both sides the anchor blocks are arranged as gravity based buried structures. The layout is slightly different on the two sides due to local soil and terrain conditions.

Tender design
Load combinations including wind or earthquake loading are governing for the design of the bridge. The bridge is designed to be aerodynamic stable for wind speeds at deck level up to 75 m/s, and with regard to earthquake it can resist peak ground accelerations up to 6.3 m/s². As part of the tender design a global 3D analysis model of the bridge structure was established using COWI’s in-house developed program IBDAS. The analyses included static as well as dynamic analyses – e.g. dynamic wind analyses, seismic analyses by spectral response spectrum and seismic time histories, accidental actions like rupture of a hanger and comfort analyses for train passengers.

The tender proposal prepared by COWI and ATI Impregilo proved to be the winning scheme and the contractor has signed the contract.

Services
- Pre-bid investigations in order to evaluate possible savings.
- Tender design of the bridge structure including all structural elements, mechanical, electrical and railway installations and life cycle cost studies

Project period
2003 – 2005

Parties
Client: ATI Impregilo
Designer: COWI
High Coast Bridge, Sweden

The High Coast Bridge carries the European interstate highway E4 and crosses the river Ångermanälven about 500 km north of Stockholm. With a main span of 1,210 m the bridge is one of the largest suspension bridges in Europe. The overall length is 1,800 m including side spans of 310 and 280 m. The bridge is designed to carry a dual-lane highway, although the effective width of 17.8 m will make it possible for it to carry a four-lane highway in the future. The bridge has a minimum clearance under the main span of 40 m.

Design
The experience gained by COWI through the design of the Great Belt East Bridge has been useful in the design of the High Coast Bridge. As a result a 4 m high and 22 m wide single-cell box girder was designed, a low span to sag ratio of 9.5 was chosen, a cable distance of 20.8 m was applied and a central fixation between cable and girder was arranged in order to obtain the best performance. All structural elements were examined by FEM-analyses.

Pylons
Extending to a maximum level of 178.5 m the pylons are plane frame reinforced concrete structures with transversely inclined legs featuring two transverse beams. As a result of an optimised technical and aesthetic design the pylons are placed directly into the water. Consequently, the pylons needed to be strengthened to withstand ship collision impact from vessels up to 40,000 tons displacement.

Superstructure
The bridge girder is continuous from abutment to abutment leading to a 1.8 km expansion section. A rigid central fixation is introduced at mid-span between the main cables and the bridge deck to control the differential horizontal movements. The continuous girder concept leads to a simple arrangement at the pylons, reduced installation and maintenance costs for the expansion joints and improved vertical and horizontal stiffness. The interior of the box girder, including the suspender anchorages, is protected against corrosion by dehumidification.

Aerodynamic design
The scenic beauty of the surrounding landscape and the severe winters with risk of snow and ice accumulation were decisive environmental factors in the design of the bridge. The suspension span is the longest built at such northerly latitude and the risk of icing and heavy snowfall required special attention regarding aerodynamic stability. Accumulated snow and ice may alter the cross-sectional shape of the girder, which, in turn, will alter the aerodynamic behaviour of the bridge. Consequently, the girder cross-section has been shaped to minimise areas prone to snow accumulation, particularly close to the edges.

Experimental verification
Experimental verification of natural frequencies and structural damping has been carried out at the completed bridge. Damping measurements have been analysed and the results indicated a clear amplitude dependence of the damping of torsional modes.

Services
- Tender design
- Detailed design
- Wind engineering
- Technical follow-up during construction
- Dehumidification of main cables

Project period
1991 – 1997

Parties
Client: The Swedish National Road Administration through Kjessler & Mannerstråle
Cable-stayed bridges

COWI has a track record comprising many world-class cable-stayed bridges for both road traffic and railway traffic and is involved in detailed design and design check of world-record cable-stayed bridge projects.

The maximum span of cable-stayed bridges have increased significantly over the years and COWI has been involved in most of the record-breaking cable-stayed bridges.

Road bridges

Back in 1986 COWI’s subsidiary in North America, Buckland & Taylor Ltd., designed the 465 m main span Alex Fraser Bridge in Vancouver, Canada. Later COWI was involved in the design of the record-breaking Normandy Bridge in France and the Stonecutters Bridge in Hong Kong. Design review and construction consultancy is carried out for the Sutong Bridge in China. The Stonecutters and Sutong bridges will both have a main span of more than 1000 m.

Road and railway bridges

COWI has also carried out the design for the Øresund Bridge, the world’s longest cable-stayed bridge span for combined road and railway traffic.
Stonecutters Bridge, Hong Kong

Stonecutters Bridge across the Rambler Channel is part of the Route 8 project in Hong Kong, an east-west expressway linking Hong Kong international airport, Chek Lap Kok at Lantau and the urban areas of the Kowloon peninsula. COWI assisted the Highways Department with a detailed feasibility study with special attention to the aerodynamic response and stability of a long span cable-supported bridge. Unlike the other major bridges of Hong Kong, Stonecutters Bridge will be clearly visible from the populated areas of west Kowloon and Hong Kong Island. The Highways Department of Hong Kong realised the potential of the site, with the dramatic setting for a world-record cable-stayed span in one of the busiest harbours in the world, and decided to procure the design concept through an international design competition.

Design competition
COWI and Ove Arup and Partners in Hong Kong worked jointly to organise the design competition for the Stonecutters Bridge. An independent technical evaluation of Stage 2 submissions was performed by COWI and included: Structural and aerodynamic adequacy check of girders, stay cables and towers by means of IBDAS and DVMFLOW.

Detailed design
The winning project of the design competition was a cable-stayed bridge with a record main span of 1,018 m. The main span is supported from two single central towers both placed on land providing a clear entrance to the container port with a vertical clearance of minimum 73.5 m. The 53.5 m wide bridge deck consists of twin box girders connected by cross-girders. The stay cables connect to the outside edges of the deck only. The deck is in steel in the main span and 50 m into the first back span while the rest of the back spans are in concrete.

COWI together with Arup won the prestigious contract of detailed design and construction supervision of the bridge. COWI is responsible for the design of towers, steel superstructure and stay cables. Furthermore, COWI has carried out the global analyses and supervision of the extensive program for wind tunnel testing including interpretation of the results. COWI has designed bridge equipment and the structural monitoring system.

The detailed design of the bridge has been particularly challenging:
• it is the first detailed design of a cable-stayed bridge with a span over 1 km
• the site is exposed to typhoon winds
• the busy harbour puts severe restrictions on construction operations
• the scope for structural modifications was limited as the overall appearance of the winning project of the design competition had to be maintained

The construction of the bridge will be completed in 2010.
The 7,844 m long bridge between Sweden and Denmark includes the world’s longest cable-stayed bridge span for combined motorway and railway traffic.

The bridge crosses the international navigation route with a main span of 490 m and two side spans of 160 m and 141 m on each side of the main span and a height of 57 m above the sea. The approach bridges towards Sweden and Denmark are 3,739 m and 3,013 m, respectively.

**Superstructure**

The girder for the cable-stayed bridge is a composite truss in steel and concrete. The concrete top deck carries a dual two-lane motorway with emergency lanes and the lower deck of the steel truss carries a two-track railway.

The approach bridges with 140 m spans have a two-level composite superstructure with a steel truss incorporating an upper concrete roadway deck and lower steel cross-beams with a concrete railway containment.

**Pylons and piers**

The concrete pylons are 203.5 m high and founded on limestone. Prefabricated caissons are placed at a foundation depth of approximately 15 m, and the pylon shafts are cast in place. Artificial islands are established around the pylons and near-by piers to protect against ship impact. All caissons, piers and pier shafts are prefabricated onshore and assembled offshore.

**Design and construct**

The contract was a design and construct contract which means that the contractor is responsible for both design and construction. The Skanska-lead consortium Sundlink Contractors HB entrusted the bid design, the basic and detailed design and endorsement of the construction work to the CV Joint Venture COWI and Sweco of Sweden with COWI as lead partner.

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**Services**

- Bid design
- Basic design
- Detailed design
- Endorsement of the construction works

**Project period**

1994 – 2000

**Parties**

- Bridge authority: Øresundskonsortiet
- Contractor: Sundlink Contractors HB: Skanska AB (S) Hochtief AG (D) Højgaard & Schultz A/S (DK) Monberg & Thorsen A/S (DK)
- Designer: CV Joint Venture: COWI A/S (DK) Sweco AB (S)
The Busan-Geoje fixed link is a major infrastructure development in the south-eastern part of Korea. It will provide easy access between metropolitan Busan and Geoje Island. The Busan-Geoje fixed link has a total length of 8.2 km and comprises three main parts: two bridges (Lot 1 and Lot 2) and a 4 km long immersed tunnel (Lot 3). These main elements are separated by two intermediate islands.

The design was prepared directly for the contractor providing the opportunity to conceive a cost-efficient structure that was optimised to suit the contractor’s methods and equipment from the beginning. Large scale prefabrication and the erection of large elements were major considerations in the design development. Furthermore, a fast track approach – with concurrent design, approval and construction – was adopted to minimize the project implementation time.

The link is located on open sea and concurrent high wind and wave loads were governing factors for the design. Each of the two bridge sections consists of a cable-stayed bridge and approach bridges. The cable-stayed bridge in Lot 1 has three pylons and two main spans of 230 m, while Lot 2 has a traditional two pylon cable-stayed bridge with a main span of 475 m.

### Superstructure
The bridges have traditional plated steel-concrete composite decks that will carry a four-lane motorway. In addition, there is a climbing lane in one direction in Lot 2. The cross-section and the fairings of the cable-stayed bridges were optimised by extensive numerical simulations and wind tunnel testing.

### Pylons
A distinct feature of the bridges is their diamond shaped pylons with curved legs. The shape of the pylons provides the visual appearance desired and, at the same time, the triangulated cable system improves aeroelastic stability compared to a layout with more traditional H-shaped pylons with vertical cable planes.

### Foundations
The bridges rest on direct foundations consisting of concrete caissons formed by a cell structure on a thick base slab, except for two pile foundations with inclined 2 m reinforced concrete piles. The design for ship impact was based on a probabilistic approach analysing the effect of future traffic scenarios with ships up to 60,000 DWT crossing the alignment. Numerical simulations and physical testing were used to determine wave loads and to optimise the scour protection.

### Prefabrication
In two prefabrication yards caissons, pier shafts and the approach bridge girders are prefabricated. The caissons are transported to site by floating dock and installed by a 3,000 t floating crane which is also used to transport and install the other parts.

### Technical follow-up during construction
During the construction COWI assists the Contractor to assess design changes and further optimise the design with regards to speed and construction methods. Furthermore, COWI reviews temporary structures and carries out the camber control for the pylons and the cable-stayed bridge girder.
The Sutong Bridge will cross the Yangtze River upstream from Shanghai and will carry a six-lane highway with emergency lanes. The total length of the bridge will be 6 km. The main bridge will be a cable-stayed bridge with a world-record breaking 1,088 m main span.

**Special fairway bridge and approach bridges**
The special fairway bridge is a rigid frame concrete bridge with a main span of 268 m. The height of the girder is 15 m at the piers and 4.5 m in the centre of the main span. The bridge provides a navigational clearance of 220 m horizontally and 39 m vertically. The approach bridges are concrete girder bridges with spans varying between 42 m and 75 m.

**Cable-stayed bridge**
The 1,088 m main span cable-stayed bridge provides a navigational clearance of 891 m horizontally and 62 m vertically in the main span and 220 m horizontal clearance in one side span on each side. The pylons are 306 m high inverted Y concrete pylons. The superstructure is a closed steel box girder with an overall width of 40 m and a height of 4 m.

The pylon foundation consists of a total of 131 large diameter bored piles with a diameter of 2.8 m reaching a depth of approximately 120 m.

The aerodynamic behaviour of a 1,088 m main span cable-stayed bridge is a critical issue and significant efforts were required to document the adequacy of the design, including parallel wind tunnel studies and numerical simulations with COWI’s in-house developed programmes DVMFLOW and IBDAS.

Due to strong currents significant scour was expected in the Yangtze River around the foundations. It was consequently decided to establish scour protection around the pylons. COWI prepared the basic design for the protection and specified the model tests to be carried out. The final design was subsequently reviewed and COWI further provided consultancy on the construction of the scour protection.

**Services**
- Design assistance and design review of cable-stayed bridge and special fairway bridge
- Design of scour protection
- Aerodynamic investigations
- Consultancy during construction, including risk management and health and safety
- Review of construction method statements
- Independent check of temporary structures
- Consultancy and check of construction control calculations
- Design review of structural health monitoring system

**Project period**
2003 – 2007

**Parties**
Client: Jiangsu Province Sutong Bridge Construction Commanding Department
Girder bridges

COWI has designed numerous girder bridges in concrete, steel and composite with provision of consultancy services in all phases of projects.

Complex shapes & consistent FEM-modelling

The IBDAS in-house design tool has been developed to assure complete compliance between complex geometric shapes of concrete and reinforcement designs and the three dimensional finite element analyses. Complex 3D reinforcement details can be produced by the model to verify constructability at congested areas with dense reinforcement.

Code verification

Design verification in accordance with most common international bridge design specifications as e.g. EuroCodes, AASHTO and BS is an integrated facility in the IBDAS-system.

Service life design

New rational probability-based methods are applied for service life design of structures - similar to strength design – where COWI's expertise in durability is widely utilised. COWI's extensive experience with operation and maintenance of bridge structures is also utilised in the performed life cycle cost assessments.

Innovation

Other new methodologies have been introduced in bridge design by COWI, e.g. fatigue design of tubular joints in Swedish railway bridges, based upon offshore design codes and hot spot stress analyses.

Prefabrication

COWI has gained valuable experience in designing bridge structures that are well suited for industrialised prefabrication and possesses the skills to combine the requirements for structural layout, construction yard capacities, and transportation and construction methods into durable and competitive designs.

Confined sites with heavy traffic

The experience gained in prefabrication is also often utilised for projects with very confined space and heavy traffic when bridge replacement is necessary.

Constructability & winning bid design

The COWI staff comprises designers with significant experience in construction engineering for major bridge projects supplemented with broad site experience, and we have been very successful in preparing winning bid designs for contractors based upon a careful consideration of the contractors’ strengths and preferences and subsequent implementation into the design.

References

Concrete
- Årsta Bridge, Sweden
- Alssund Bridge, Denmark
- Vejle Fjord Bridge, Denmark
- Sitra Causeway, Bahrain

Steel
- Great Belt approach bridges, East Bridge, Denmark

Composite
- Farø Bridges, Denmark
- Brygge Bridge, Denmark
- Råån Railway Bridge, Sweden
- Øresund approach bridges, Sweden – Denmark

Concrete
- Årsta Bridge, Sweden
- Alssund Bridge, Denmark
- Vejle Fjord Bridge, Denmark
- Sitra Causeway, Bahrain

Steel
- Great Belt approach bridges, East Bridge, Denmark

Composite
- Farø Bridges, Denmark
- Brygge Bridge, Denmark
- Råån Railway Bridge, Sweden
- Øresund approach bridges, Sweden – Denmark
Among the bridge engineering staff in COWI there is a group specialised in moveable bridges: swing, bascule and lift bridges.

**Clients’ requirements**
Ship traffic and ship collision analyses are performed internally and applied as a firm basis for specification of functional and design requirements for the bridges – including protection structures.

**Aesthetics**
COWI has strong relations to leading bridge architects and a proven ability to develop designs for moveable bridges of high aesthetic standards.

**Multidisciplinary design approach**
The structural specialists provide the designs that meet the clients’ requirements and expectations in a multidisciplinary approach, where dedicated mechanical and electrical engineers are providing the functional specifications and designs for the systems that make the bridges moveable. This comprises all lifting systems supplemented with the necessary monitoring and control systems for both the lifting gear and the road, rail and shipping traffic.

Structural monitoring systems are often included in order to enable a systematic surveillance of the structures and collection of data for inspection and maintenance planning.

**Structural analyses**
All kinematic and dynamic aspects of the designs will be analysed by in-house developed software including, for example, wind buffeting analyses and wave climate and load effect analyses.

**Inspection and maintenance**
Continuous involvement in planning, inspection, maintenance and repair works on existing moveable bridges is the basis for broad and specialised experience with COWI’s staff that is available to our clients.

The detailed experience with actual operation and performance of moveable bridges is also utilised in the design where operation and maintenance aspects are carefully integrated in the designs based upon service life design and life cycle cost analyses.

**Repair and strengthening**
COWI has prepared repair and strengthening designs for bascule bridges with dense traffic. Removal of entire bridge parts, rehabilitation and strengthening at remote sites and reinstallation enabled a cost-efficient approach which, at the same time, had the least negative implications for traffic.
**Urban bridges**

Inhabitants get very close to bridges in urban environments and requirements to such bridges are, consequently, stricter in respect of aesthetic qualities.

**Aesthetics**

COWI has an extensive tradition for collaboration with recognised architects when designing bridges – in particular urban bridges in order to make the bridges fit into the existing environment.

**Lightness and transparency**

Urban bridges are located in confined space and should be light, transparent and elegant structures to avoid an intrusive appearance.

**Landmarks**

Bridges may achieve landmark qualities when they are designed with unique characteristic shapes and may become points of attraction for the citizens and visitors to the city.

**Functional sculptures**

Of course the bridges have a function and if the structural elements can be given simple geometric forms, the final result may have the supplementary quality that the bridge becomes a sculpture and thereby adds quality to the inventory of the city.
Munksjö Bridge, Sweden

Lusail Bridges, Qatar

Aagade Bridge, Denmark

Nelson Mandela Bridge, South Africa
Project implementation

Economy, financing and organisation

COWI provides policy planning and advice as well as management consulting in relation to both project decision and project implementation.

Services

We provide:

- Assessment of demand impacts of service changes and users willingness to pay for services based on advanced customised market research
- Strategic demand modelling to establish an overall demand for the infrastructure and the effects of different service and toll levels
- Economic and financial project analysis of project alternatives to assist in the process to select the optimal project type and alignment within the frame of project goals defined by the customer
- Independent assessment of decision basis, budget assumptions and risk management for large infrastructure projects

Project delivery

We advise on:

- Project finance and organisational set-up for large projects including the various ways of financing infrastructure projects
- Assessing the potential of public-private partnerships for specific projects considering project risks and revenue potentials

Organisational set-up for public-private partnership project

Tolling booths, Denmark
Feasibility studies for fixed links

The feasibility study for a fixed link will typically result in a selection of:

- Alignment
- Structural concept
- Project delivery strategy

**Challenge**
The main challenges of the feasibility study are thus to establish a well-founded basis for the decisions, which takes into account and integrates technical, environmental, social, economic and financial aspects.

**Expertise**
COWI offers in-house expertise for all general aspects related to fixed links:

- Management capabilities for the integration of many complex disciplines
- A multidisciplinary expertise
- Extensive experiences with causeway links worldwide

**Multidisciplinary services**
For the feasibility study of a fixed link, COWI can offer a comprehensive range of services in:

- Surveys: topography, bathymetry, traffic, stated preferences
- Site investigations: soil conditions, geology, geophysics, meteorology & hydrography, ecology & environment
- Studies: navigation, construction, operation & maintenance, financing, project delivery methods, procurement strategies
- Modelling: traffic, hydraulic, aerodynamics
- Sketch and conceptual design: bridges, tunnels, marine works, border facilities, mechanical & electrical systems, railways and roads
- Assessment: safety & risk, design basis, environmental impact, cost estimation
- Management support: support to client, risk management, reporting, presentation
- Selection of solutions: selection process, decision modelling, sensitivity studies, workshops

Illustration: D+W

Integrated numerical modelling of global regional and local hydraulic conditions.
Qatar-Bahrain Causeway

Mapping of sea grass, Qatar-Bahrain Causeway

Proposed Fehmarn Belt Bridge, Denmark – Germany
**Design**

**State-of-the-art knowledge**
The first cable-supported bridges were designed by COWI back in the 1950’s. COWI is today recognised for its state-of-the-art knowledge on design of major bridges.

**Innovations**
Today’s innovations are often tomorrow’s best practices. This is the case with dehumidification of the interior of box girders for corrosion protection, first introduced by COWI on the New Little Belt Bridge, Denmark in 1970. The application of numerical models for aerodynamic analyses of structures is another example.

**Resources and tools for design**
A continuous flow of major bridge projects ensures a large core team of bridge engineers dedicated to major bridge design work. This ensures a highly flexible and up-to-date resource base and, at the same time, keeps us competitive in terms of rational design approach. Our Integrated Bridge Design and Analysis Software (IBDAS) facilitates a high quality fast-track design with consistency between analyses and project deliverables.

**Design basis**
COWI develops the design basis for major projects according to functional requirements and the codes and standards selected including risk analysis and reliability-based calibration of safety factors.

**Construction aspects**
Construction and erection engineering form a natural part of our services to contractors. A competitive market requires cost-effective designs. Bid designs by COWI prepared for contractors are always developed in close cooperation to reach the winner position.

**Life cycle**
COWI is also heavily involved in maintenance and rehabilitation works on major bridges. The experience gained from working with the existing bridges is extremely important in developing tomorrow’s design concepts for enhanced durability.
Design check and consulting

For complex bridge projects the bridge owner or investors often require an independent design check or a design review and, occasionally, this is extended to also include consulting or value engineering services.

The owner hereby obtains an independent assessment of the bridge to find out whether it is reliable, durable and economical.

Design experience
COWI has a long track-record within design and supervision of world-class cable-stayed and suspension bridges. This experience makes COWI the perfectly qualified partner for independent design check of complex bridges.

Design check and review
COWI has a strong toolbox to analyse complex bridge structures with IBDAS providing facilities for analysis of all important bridge design issues combined in one key tool.

COWI’s team of specialist bridge designers will be able quickly to identify critical issues for a given bridge structure and have the structures modelled and analysed in an highly qualified and extremely efficient manner, thus providing our clients with very competitive services that, at the same time, can be provided within tight time-schedules.

Furthermore, our expertise in construction engineering will be beneficial for assessing the constructability of the proposed designs.

Consulting
As a supplementary service COWI also provides consulting services to bridge owners or investors during the entire design and construction process. The services may comprise:

• Specialist advice on specific issues provided as technical notes or reports
• Discussions between COWI specialists and relevant staff from the client – in site meetings or as teleconferences
• Current advice via permanent or periodic presence of COWI staff at design offices or at site
The selection of construction methods is of crucial importance for the economical and timely completion of bridge projects.

Our engineers possess extensive expertise in construction and erection engineering and we can provide the required assistance throughout the construction process from initial planning of the project to supervision during erection.

**Erection schemes**
Depending on the constraints of each project location and the time available for the construction process the methods used have an important influence on the success of the project.

Within COWI we have accumulated know-how concerning construction and erection methods which have been used for construction of major bridges.

The right combination of methods is one of the main keys to a successful bridge project.

**Logistics**
The logistics of prefabrication and erection is another important issue during the construction phase for major bridges.

We can provide know-how concerning the lay-out and construction methods for prefabrication yards as well as the overall logistical planning of the construction process.

**Temporary structures**
The construction of bridges calls for interim structures to support the bridge elements during the erection stages and very often custom-made erection equipment for the installation of the bridge elements.

We can provide conceptual and detailed design of a variety of temporary structures and equipment including:
- Temporary support structures
- Cranes and hoists
- Girder connection and fixation systems
- Erection equipment for cable installation
- Form travellers
- Erection gantries
- Skidding systems

**Erection**
During the erection of a bridge each step of the erection needs to be controlled carefully to obtain the required distribution of forces and geometry.

With our in-house developed computer programme IBDAS, COWI can provide step-by-step calculations for the erection of bridges and all necessary follow-up services.

The effects of cast-in stresses and deformations, creep and shrinkage of concrete and construction tolerances are included and assessed with the programme.

*The Normandy Bridge, France*
Construction management

The experience from 40 years of construction management on a worldwide basis is accumulated in COWI including disciplines like:

Contract management
Throughout the contract period the construction management organisation will have a need for an in-depth knowledge of the contract as to legal and commercial aspects.

Progress
Monitoring the progress of the project in all aspects is of major importance for the construction management. Progress analyses are a prerequisite for decisions on actions to mitigate threats against milestones and budget.

Cost control
Monitoring the economical development related to the works progress is essential for decisions on possible mitigations against an overrun of the budget. This includes agreed budget changes as well as recorded claims.

Risk management
Construction of an infrastructure project of a certain magnitude implies considerable risks for e.g. environment, third parties, time schedule and economy. Risk assessment during the construction period is an important tool for the construction management giving part of the basis for mitigating actions against major accidents as well as delays in production. An overall risk assessment includes construction risks, time and economy.

Authorities
The objective of the authority management is to ensure timely and correct communication regarding applications, permissions and approval of use.

Third parties
The objective of the third parties’ management is to ensure that all parties influenced by the project, but not directly included in the management hereof, are well informed and able to make them heard.

Technical follow-up
The objective of the technical follow-up management is to ensure that the construction management forms a consistent estimate of the optimal handling of a technical problem being the responsibility of the management.
Site supervision

The experience of site supervision on a worldwide basis is accumulated in COWI, including disciplines like:

**Preconstruction tasks**
- Project review with the contractor
- Review of performance security
- Review of the contractor’s insurance policies
- Review of the contractor’s work and payment plan
- Review of the contractor’s quality, environmental, health and safety plan

**Tasks during construction**
- Review of the contractor’s method statements, work procedures and control plans
- Safety issues

**Tasks at project completion**
- The contractor’s application for taking over
- Tests on completion
- As-built documentation
- Taking over certificate

**Tasks after project completion**
- Statement on completion submitted by the contractor
- Completion payment certificate
- Defects notification period
- Performance certificate
- Final payment certificate

**Documentation**
Upon completion of the construction works, the site supervision has delivered a comprehensive documentation of the quality of the project including possible changes agreed during the period of construction.

**Operation and management**
This documentation is an important part of the basis for the following operation and maintenance management of the project.

Naini Bridge, Allahabad, India
Operation and management

Major public assets as roads and bridges need efficient management, administration and operation in order to utilise resources in an economic and technical optimal manner.

Over a period of more than 20 years COWI has developed an asset management approach based on practical experience from planning, budgeting and handling of both short- and long-term operation and maintenance and rehabilitation works.

Concept

Operation management normally comprises:
- Administration with a description of organisational responsibility for operation and maintenance and relations to external parties
- An inventory with a systematic filing system for all inventory data
- Management tools including systems developed to fulfill the need for information to the:
  - public
  - management
  - bodies engaged in the operation and the maintenance
  - managing of tasks including time, economy, quality, safety and environmental matters
- Traffic and technical operation consultancy in preparing procedures and instructions for the daily operation

COWI has extensive experience in designing maintenance works to be carried out during traffic flow in urban environments and traffic near the capacity limit. New and innovative solutions are required to maintain the structures.

- Inspection and maintenance activities aim to maintain the structures by preventive maintenance with a minimum of corrective maintenance. The daily maintenance comprises principal and special inspections, preventive and corrective maintenance and monitoring
- Equipment and materials including advise on necessary maintenance equipment and tools with instructions about use and servicing

COWI has been involved in designing equipment for inspection of bridge girders, main cables and pylons.

Maintenance management systems

Efficient computerised systems are needed in order to support the management concept and to optimise the use of allocated funds amongst all the components of infrastructure elements.

COWI has more than 20 years of experience in implementing both management concepts and computer tools e.g. in Singapore, China, Thailand, Spain, Denmark and Uruguay.
Re-evaluation and rehabilitation

Bridge condition
During the lifetime of a bridge the use may change, e.g. the loads acting on the bridge may increase, or the bridge may be subject to deterioration, e.g. corrosion, which influences the ability to fulfill its purpose with sufficient safety. Re-evaluation, in many cases, justifies the continued use of the bridge and thus ensures the owner a significant increase in return of investment.

All phases
In connection with as-built verifications, operation and maintenance, inspections and condition assessments of concrete and steel structures we carry out all steps of the investigations - right from the visual inspection to special investigations where we evaluate the load carrying capacity and the safety of structures. In this way we make sure that the technical evaluations are coherent.

ISO9001 certified laboratory
We have our own materials laboratory including a wide range of testing equipment for site measurements. We find the causes of the problems, assess the consequences and propose repair strategies. By using our own laboratory we can even determine the condition of different structures and the extent of their deterioration. Based on the causes of the problems we assess the consequences and propose repair strategies.

Repair strategies and updating service life design
COWI designs the durability of concrete structures based on fixed service life requirements, the environment and our knowledge of deterioration mechanisms and the rate with which the deterioration takes place. Our competence on deterioration and design is gained based on participation in research and development projects and gained from experience with investigating numerous deteriorating structures. Our design and repair strategies are based on technical, financial assessment of different durability strategies in relation to costs during the entire expected service life of the structure (life cycle cost analysis).

Reliability-based re-evaluation
For deteriorated major bridges COWI has experience in re-evaluation based on a rehabilitation design basis uniquely developed for the considered bridge. This involves actual loading conditions, calibration of partial safety factors and updating using inspection results. Such an approach facilitates a very flexible rehabilitation project by minimising traffic interruptions and inspection needs.

Competencies
Selected competencies related to re-evaluation:
- Deterioration modelling
- Testing of materials and structural testing of bridge structure
- Service lifetime assessment
- Inspection using state-of-the-art inspection techniques
- Optimal plans for inspection, maintenance and repair needs
- Structural reliability
- Calibration of bridge specific loads
- Calibration of safety factors
- Reliability updating based on inspection or test results
- Advanced numerical analysis
- Development of national guideline for probability-based assessment of bridges
- Chloride-induced corrosion
Decommissioning

At the end of a bridge’s operational life, decisions regarding its decommissioning shall be taken. The owner faces a difficult choice between various removal options influenced by uncertain technical, environmental and safety aspects.

**Damaged structure engineering**
Structures are occasionally damaged by exceptional loads as a result of natural disasters, actions of war, rare accidents or component failures. Damaged structures require careful considerations to evaluate damage loads and imminent risk, as well as to establish the extent and types of repair to suit the remaining lifetime of the structure.

**Replacement**
Until recently, the existing Manama-Sitra Causeway was the main link between the capital Manama on Bahrain Island and Sitra Island. The replacement project was initiated to replace the two old marine bridges which had insufficient load carrying capacity with the new Sitra Causeway in order to increase the traffic capacity.

**Risk-based assessment**
To facilitate the owner’s choice of a removal option, COWI can carry out a quantitative comparative risk assessment of various removal options, including partial and complete removal options. The method statement of each removal option is broken down into a number of sequential activities. For each activity the main hazards are identified and their probability of occurrence are assessed from detailed technical background documentation and in expert workshop sessions.

**Bayesian networks**
A risk model is established using object-oriented Bayesian networks - a class of probabilistic models well suited for handling interdependent variables. The removal options are compared with respect to technical and personnel risk as well as environmental impact. The technical feasibility of the removal activities includes quantification of major accident probabilities and schedule/cost problems. Personnel safety is evaluated in terms of fatality risk during e.g., diving, cutting or lifting operations.
Advanced bridge design calls for highly specialised analysis tools to meet today’s requirements of high quality, detailing level, efficiency and competitiveness.

COWI’s in-house developed IBDAS is a state-of-the-art FEM-program and CAE tool, which has been developed to optimise design and analyses of new and existing bridges and to analyse construction processes.

**Important features**

IBDAS has facilities for (selected examples):
- Linear static analyses
- Geometric non-linear analyses
- Plastic analyses
- Dynamic wind analyses using Davenport’s buffeting theory
- Time history dynamic analyses
- Seismic response spectrum analyses
- Multi-support seismic response spectrum analyses including varying support conditions, coherence etc.
- Train-structure interaction analyses including comfort analyses and derailment risk
- Buckling and stability analyses
- Float stability analyses for caissons
- Probabilistic reliability analyses
- Pile foundation analyses

**Load combination**

Bridge live loads and other loads can be modeled and maximum load effects automatically determined based on simple as well as complex load combinations.

**Verification**

Design verifications can be performed for truss, beam and shell elements for various design codes and, at present, the following have been incorporated:
- Eurocodes
- BS 5400
- AASHTO
- CEB-FIP model code
- Scandinavian & German codes

**Construction stages**

IBDAS is capable of modelling the exact sequence of construction stages including such activities as
- Casting of structural parts
- Erection or removal of structural parts
- Stressing/slackening of tendons
- Changes in support conditions
- Placing of removing temporary loads

Associated time indications enable IBDAS to keep track of and determine time-dependent phenomena such as creep, shrinkage and relaxation.
COWI uses other state-of-the-art numerical models and tools in all phases of projects and COWI staff has profound experience with their application.

**Hydraulic modelling**

Environmental conditions in respect of wave and current loads are analysed by simulation of hydrodynamics of the oceans, coastal regions, rivers etc.

MIKE 21 is a package of programs to simulate waves, currents and sediment transport in the marine environment used by COWI staff to analyse the environmental load conditions at bridge sites. The model is used for tidal motion and flow, and for storm surge set-up due to wind and barometric pressure. It is further used to calculate wave conditions in deep and shallow water - including tsunamis - based upon wind data and to simulate wave disturbances in enclosed waters.

**Soil modelling**

For bridge foundations COWI generally makes extensive use of advanced computational methods for the analysis of foundations. The analyses are utilising COWI’s IBDAS system supplemented by general purpose finite element programs as, for example, ABAQUUS and PLAXIS, or more specialised pile and pile group software, such as LPILE, GROUP and MPILE. The analyses cover various purposes:

- Calculation of internal forces and moments
- Verification of bearing capacity
- Verification of interface load transfer capacity
- Verification of overall stability
- Prediction of foundation movements
- Prediction of ultimate carrying capacities
- Prediction of energy dissipating capabilities

**Numerical analysis**

ABACUS strain analysis for an outrigger supporting the cable-stay anchor at the Øresund Bridge, Denmark – Sweden

Mike 21 model simulating wave heights for the Busan-Geoje fixed link location

PLAXIS is a finite element program specifically developed for numerical analysis of geotechnical and underground structures and soil-structure interaction
Aerodynamics and wind engineering is of central importance in the design of flexible structures such as bridges, towers and gantry structures. Wind loads and aerodynamics often become governing factors for design and operation of such structures.

Capabilities
COWI maintains front-line expertise within the following fields:
- Wind climate
  - design and supervision of field wind measuring systems
  - extreme wind and turbulence analyses
  - drafting of design specifications
- Wind tunnel testing
  - design, planning and supervision
  - terrain model tests
  - section model tests
  - full aerelastic model tests
  - high Reynolds' number tests
- Computer simulation – DVMFLOW
  - wind loading
  - aeroelastic stability
  - vortex shedding action
- Design
  - bridges
  - windbreaks and shelters
- Mitigation measures
  - cable vibrations
  - aerodynamic instability and vortex shedding excitation
  - guide vanes
  - tuned mass dampers
- Full-scale measurement
  - structural dynamics and wind response

Numerical methods
The COWI aerodynamics group has revolutionised the field of bridge aerodynamics through the introduction of numerical methods. Our simulation code DVMFLOW, introduced almost 10 years ago, has set new standards for design stage wind engineering of bridges and has been applied in the design and check of more than 20 cable-supported bridges worldwide.

DVMFLOW has been calibrated against numerous wind tunnel tests.
Large amplitude cable or girder vibrations initiated by wind loading can, in some cases, be foreseen already at design, while, for other structures unexpected environmental conditions as ice formation can cause unwanted vibrations.

**Cable-stay damping**

For cable-stayed bridges measures for damping cable-stay vibrations initiated by wind is often needed. COWI has through analysing and solving problems with cable vibrations due to “ice galloping” at the Danish Great Belt, East Bridge and Øresund Bridge built up extensive state-of-the-art knowledge within damper design. The work involved unconventional signal analysis of the vibration data, comparisons with analytical/theoretical models and assessment of the fatigue damage sustained. Some of the designs have even been backed by tuned mass dampers on selected stay cables.

**Tuned mass dampers**

At the construction of long span cable-stayed bridges temporarily TMDs are often needed to prevent large girder oscillations prior to girder closure. Bridge profiles sensitive to vibrations from wind loading or extreme wind conditions can also require installation of TMDs in girders or pylons in order to damp vibrations.

**Damper design**

Typically, a cable damper or TMD design study involves:

- Calculation of bridge or cable dynamics
- Calculation of dynamic wind loads
- Determination of TMD parameters
- Concept for mechanical arrangement of damper or TMD units
- Prediction of damper or TMD response and reduction of stresses in bridge girder

**Services**

- Concept development
- Monitoring and signal analysis
- Analytical/theoretical models
- Detailed design of cable dampers and tuned mass dampers
- Installation supervision
- Testing and verification

*Stabilisation of the bridge girder during erection by use of temporary TMD. The Normandy Bridge, a 836 m main span cable-stayed bridge, France*
The safety related to the operation of bridges can be rationally managed in a process that runs in parallel with the initial investigations, design basis development and conceptual studies.

**Risk policy**
The process involves formulation of safety goals including screening of potential risks, selection of the main types of risk of concern and a formulation of the corresponding acceptance criteria.

**Risk analysis**
A preliminary identification and qualitative screening and ranking of the risks can be used to select the main risks to be quantitatively assessed.

The process involves means of achieving the safety goals including quantitative risk analyses of accidents, their spectrum of consequences, the corresponding probabilities of occurrence and the selection of design criteria.

Examples are arrangement of navigation channel and navigation span such that ship collision to bridges will not occur frequently, but only as extreme events as a result of failures and errors.

**Risk mitigation**
In the case that the risk acceptance criteria are not initially met, risk-reducing measures are identified and their risk-reducing effects are assessed.

**Operational risk management**

Risk allocation
In this way it is possible for the client/owner to select the most suitable concept and corresponding design basis in the sense that the protection against accidents is based on his preferred balance of costs and risks.

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**General hazards**
- Road accidents
- Rail accidents
- Ship collision to bridges crossing waterways
- Earthquake
- Scour
- Fire and explosions
- Extreme environmental impact such as ice impact, high waters, large waves and typhoons

**Consequences**
- Loss of bridge structure
- Injuries and loss of lives
- Disruption of bridge traffic until remedial work has been made
Construction risk management

Bridge construction works impose risks on those parties directly involved as well as third parties.

Risk policy
For each type of risk, specific minimum risk objectives may be defined in addition to general risk objectives.
For example, the general public should be exposed only to a small additional risk from the construction of a bridge – compared to the risk they are normally exposed to.

Risk analysis
Systematic construction risk management techniques can be used throughout the bridge project development.
The use of construction risk management from the early stages of a project may influence the selection of construction methods aiming at the reduction of the inherent risks.

Risk mitigation
Potential problems can be clearly identified and assessed such that appropriate risk mitigation measures can be developed and implemented in a timely manner, and construction methods and supervision procedures can be selected to minimise risks.

Risk allocation
The evaluation of the risks may also be used to allocate the available resources in an optimal manner.

<table>
<thead>
<tr>
<th>General hazards</th>
<th>Specific hazards</th>
<th>Consequences</th>
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<tbody>
<tr>
<td>• Contractual disputes</td>
<td>• Accidents’ occurrences</td>
<td>• Incidents and injuries to staff</td>
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<tr>
<td>• Insolvency and institutional problems</td>
<td>• Unforeseen adverse conditions</td>
<td>• Incident and injuries to third parties</td>
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<td>• Authorities’ interference</td>
<td>• Inadequate designs, specifications and programmes</td>
<td>• Damage to neighbouring facilities</td>
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<td>• Third party interference</td>
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<td>• Labour disputes</td>
<td>• Works that are substandard, slow or out of tolerance</td>
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<td>• Bad reputation</td>
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Ship collision and ship impact protection

Major bridges often cross navigation channels and ship impact may therefore become a significant hazard for the safety of both structures and users.

The risk from ship impact can be controlled preventively by increasing the navigational clearance and improving the navigational arrangement near the bridge. Risk control by protective means can be achieved externally – e.g. by installing protection islands or dolphins – or by increasing the strength of the bridge piers to resist accidental impact from ships.

Dolphin capacity
Utilisation of the full dissipative capacity of protection dolphins requires detailed 3D computer modelling to describe the significant deformations and displacements occurring during an impact.

The geotechnical modelling group in COWI has generic FEM-models and significant experience in analysis of ship impact protection dolphins and in determining the energy dissipating capabilities during the large plastic deformations.

Comparison with the results of an extensive scale model testing program conducted in the large geo-centrifuge at GeoDelft has given a strong experimental confirmation of the FEM-modelling.

COWIs advanced modelling techniques thus permit full assessment and utilisation of the energy dissipation capacity of protection dolphins.

Simulation of impact scenarios
The combined effect of an arrangement of protection dolphins is analysed in full detail using a 2D numerical simulation model that combines the dynamics of the ship and the layout geometry and response characteristics of the dolphins.

Risk analysis
Statistical data and projections on the ship traffic are combined with the simulation model to estimate the frequency that a ship will be able to pass the protection arrangement and reach a pier with a sufficient impact speed to cause collapse.

Optimization of protection layout
Iterative use of the models and risk estimation enables a systematic optimisation of the layout to achieve a cost-effective protection that satisfies a predefined or established upper limit for the frequency of collapse due to ship impact.

References
• 2nd Incheon Ship Impact Protection Project
• Arthur Ravenel Jr. Bridge (New Cooper River Bridge)
• Great Belt, East Bridge

Physical and numerical model of protection dolphins for 2nd Incheon Bridge, Korea
The overall aims for structural monitoring systems are to:

• Ensure safe structures
• Obtain rational and economic maintenance planning
• Attain safe and economic operation
• Identify causes for unacceptable responses

In short, this can be described by the application areas mentioned below.

**Design verification**
Structural monitoring systems can acquire data on loads and structural responses over long measurement periods to verify stochastic load parameters and structural response in comparison with calculated response. Short time monitoring can include forced loading on a structure.

**Maintenance planning**
Monitoring of structures can provide quantification of degradation rates and wear which are essential to a regular updating of information on structural states. This, in turn, can be used in rational planning of inspection, maintenance activities and calibration of lifetime models.

**Safety provisions**
Structural integrity of critical elements may be crucial to the operational safety of structural systems. Continuous surveillance of such elements can provide information or warnings to intervene before severe consequences emerge.

**Trouble-shooting**
Seldom and insufficiently understood responses of structures and associated load parameters (often wind) can be documented through automated measuring campaigns – often of extended duration.

**Monitoring systems**
Advances in sensor and data acquisition technology have enhanced the economical and technical feasibility of remotely controlled environmental and structural monitoring programs.

Structural monitoring systems working fully automatically with sensors in a distributed data acquisition network have been designed on the Great Belt Bridge, Naini Bridge, Stonecutters Bridge and Sutong Bridge. Wireless remote control and data control by internet browser is an integrated part of these systems.

**References**
- Busan-Geoje fixed link
- Messina, SHMS
- Sutong Bridge
- Stonecutters Bridge
- Naini Bridge
- Great Belt, East Bridge
- Normandy Bridge
Dehumidification systems were designed by COWI and established for corrosion protection of the interior of the steel box girder of the New Little Belt Bridge completed in 1970 and has since proven to be a very reliable method.

Cost efficiency
Although with a higher cost for construction the life cycle costs are significantly lower than a more traditional painting system, and it has been used on several major steel bridges for corrosion protection of the interior of steel box girders – and also main cable steel at the anchorages.

A dehumidification system can be designed and implemented at the time of construction but may also be implemented at a later stage – in case corrosion appears to be problematic.

Cable dehumidification systems
The method has been extended also to flexible main cable systems, where a wrapping of elastomeric material around the main cable and a sealing of the cable bands are providing a tight outer barrier between the moist ambient air outside and the dry air inside the cable.

The layout of a main cable dehumidification system comprises:
• Dehumidification plants, typically at pylon tops, at midspan and at the cable anchorages
• Buffer tanks at the dehumidification plants
• Monitoring of relative humidity, temperature and flow rate and control of system operation

References
Steel bridge girders:
• New Little Belt Bridge, Denmark
• Farø Bridges, Denmark
• East Bridge, Great Belt, Denmark
• Øresund Bridge, Denmark – Sweden
• Stonecutters Bridge, Hong Kong
• Normandy Bridge, France
• High Coast bridge, Sweden
• Humber Bridge, United Kingdom

Suspension bridge main cables:
• High Coast Bridge, Sweden
• New Little Belt Bridge, Denmark
• Acquitaine Bridge, France
• Hardanger Bridge, Norway
**Scour protection**

Many large bridges cross major waterways, i.e. rivers, estuaries, fjords etc. and have pylons and bridge piers founded in the water. In many cases the water is subject to currents and waves and the bed is erodible. Under such circumstances the introduction of the bridge structures changes the flow conditions causing an increase in the local sediment transport capacity and leads to scour.

Scour is a very important aspect in bridge engineering. Bridges over rivers have collapsed due to insufficient scour protection, because the scour hole became so severe that it resulted in failure of the bridge pier(s).

**Design approach**

COWI uses state-of-the-art methods in assessment and design of scour protection for major bridges with the following tasks:
- Assessment of existing situation including bathymetry, hydraulic and soil/geotechnical conditions
- Assessment of future situation including impact of bridges and estimates of scour
- Conceptual design of scour protection
- Detailed design of scour protection. COWI uses numerical (MIKE21, in-house) and physical modelling

**Design considerations**

For many bridges it is required to study the hydraulic, geotechnical and structural conditions of the situation with and without scour protection. It is important for a project that the costs for the possible scour protection pays off in terms of overall economical feasibility.

**Examples of designs**

On the Øresund link between Denmark and Sweden the scour protection consists of quarry stones, two layers on a quarry run filter.

For the Sutong Bridge in the Yangtze River where the scour potential is in the order of 30 m for the main pylons, a different approach was developed. The protection primarily consists of quarry stones. The scour protection is separated into three areas, central area, outer area and falling apron area. In the central area a temporary protection using large sand bags in approx. 3 layers was placed prior to starting the piling for the foundation of the main pylons. The piling takes place through the sand bags forming pre-protection to control scour.
**Construction materials**

**Fibre composites and stainless steel**

The Herning pedestrian bridge pushes the limits of the state-of-the-art within application of fibre-reinforced polymers. This project is the result of a research and development project initiated by the Danish road directorate.

The cable-stayed bridge has a central steel pylon and two 40 m side spans with a width of 4 m. All 16 cable-stays are made of carbon fibre-reinforced polymer (CFRP) cables, as are the six non-bonded post-tensioning cables in the bridge deck.

The reinforcement in half of the bridge deck consists of CFRP bars and stirrups. The reinforcement in the other half of the bridge deck is a combination of stainless steel and conventional reinforcement steel.

The cross-section is over-reinforced and the compression zones are confined by means of stirrups. The result is a flexural failure governed by ductile concrete crushing due to the high ultimate compression strain of confined concrete.

**Stainless structural steel**

For the Stonecutters Bridge in Hong Kong the pylon tops have been designed with a stainless steel surface in order to minimize future maintenance on the outside of the pylons and also for aesthetic reasons. Repainting of ordinary block steel would involve extensive works above the bridge deck being both costly and difficult, and restrictions on traffic during repair works would be required.

**Environmentally friendly concrete**

A Danish research project entitled “Green Concrete” has the objective to create new knowledge about environmentally friendly types of concrete and to develop technological solutions aimed at promoting the use of this type of concrete.

The project developed the following strategies:

- Cements that require less energy under production using e.g. 18% renewable fuels instead of coal
- Reduction in CO$_2$ emissions by using large amounts of fly ash (>> 20%)
- Bridge decks without surface protection (asphalt or moisture barrier)
- Combine stainless steel and black reinforcement to relax requirements to concrete

The strategies help to reduce the impact on the environment throughout the service life of the structure.

The suggested strategies were tested in a motorway bridge (2002) built by the Danish road directorate. The bridge stands as a tangible proof of the applicability of environmentally friendly concrete.
Service life design

Durability
The DuraCrete design methodology represents an intelligent use of the modern durability technology for concrete structures and can provide any required design service life for concrete bridges. The level of reliability of the design life can be selected and can be adjusted to an accepted detailing of foreseen maintenance.

Design options
Basically two different design options exist to ensure a required service life: Option A, avoid the degradation threatening the structure and option B, select an optimal material composition and structural detailing to resist the degradation for a specified period of use. The use of stainless steel in bridge zones being exposed to high chloride concentrations is considered as a highly reliable solution following design option A. The Stonecutters Bridge, Hong Kong is an example of the selective use of stainless steel in the most exposed zones. The pylons are heavily reinforced with multi-layer of ø50 mm bars. Only the outer layer of reinforcement is stainless steel, the remaining is ordinary black steel. This solution reduces the total life cycle costs due to savings in future repair and maintenance.

Refined design
Much more refined combinations of structural layout, materials selection, quality of execution, adopted maintenance strategy and level of reliability chosen to counteract the identified aggressivity of the environment are utilised today to find an optimal bridge design to the satisfaction of our clients.

Durable and reliable repairs
Also for the residual service life of repaired structures such advanced design methodologies can be used – or the simple method of avoiding the primary deterioration mechanisms can be adopted, also using stainless steel reinforcement.

Identify environments
A key issue is to identify the aggressivity of the environment. An understanding of deterioration mechanisms provides the rational basis for doing so.

Stonecutters Bridge, Hong Kong with reinforcement stainless steel

Concrete exposed to harsh marine environment

Replacement of ordinary reinforcement with stainless steel
Selected references

**Chiloe Bicentennial Bridge, Chile**
Total length: 2,634 m
Main span: A double main span with spans of 1,055 m and 1,100 m
Client: Empresa Construcción Puente Chiloé S.A. Chile
Services by COWI: Preliminary design of the main bridge structures and the electrical and mechanical installations on the bridge (2006).

**Yeosu Sandan, Korea**
Total length: 8,500 m
Main span: 1,545 m
Basic design completed: 2006
Client: Yooshin Engineering Corporation
Services by COWI: Development of bridge concept, basic design, ship collision risk analysis and design of protection structures and aerodynamic specialist studies.

**Nanjing Yangtze high speed rail bridge, PR China**
Total length: 1,248 m
Main span: 2 main spans of 336 m
Analysis completed: 2003
Client: BRDI, P.R. China
Services by COWI: Comfort analysis of cable stayed bridge, comfort analysis of steel arch truss bridge and concept review of both bridges.

**Chongming Bridge, PR China**
Total length: 9,600 m
Main span: 730 m
To be completed: 2008
Client: Shanghai Yangtze River Tunnel and Bridge Construction Development Co. Ltd.
Services by COWI: Independent design check and consultancy for cable-stayed bridge and approach bridge.

**Xihoumen, PR China**
Total length: 2,228 m
Main span: 1,650 m
To be completed: 2009
Client: Zhoushan Mainland Link
Services by COWI: Aerodynamic analysis.

**CangKou, PR China**
Total length: Qingdao Bay Crossing 25,500 m, CangKou 600 m (one of three cable born bridges included in the crossing)
Main span: 260 m
To be completed: 2011
Client: ShangDong Express Way Co Ltd.
Services by COWI: Design review.
**Suramadu Bridge, Indonesia**
- Total length: 5,000 m
- Main span: 434 m
- To be completed: 2009
- Client: P.T. Vlrama Karya
- Services by COWI: Carrying out independent design check and consultancy for cable-stayed bridge and approach bridges.

**Goha Grand Bridge, Korea**
- Total length: 900 m
- Main span: 500 m
- Completed: 2004
- Client: LG Engineering & Construction Corp.
- Services by COWI: Review of the design from construction point of view, step-by-step calculations, construction follow-up and ad hoc assistance during construction.

**2nd Incheon ship impact protection, Korea**
- Total length: 12,343 m
- Main span: 800 m
- To be completed: 2009
- Client: Samsung Corporation Joint Venture through COWI Korea
- Services by COWI: Specialist assistance, concept design, erection procedure and detailed design.

**Lusail Ring Bridges, Qatar**
- Total length: 204 m
- Main span: 129 m
- To be completed: 2011
- Client: QatariDiar Real Estate Investment Company
- Services by COWI: Supervision of marine works, marine bridge design and supervision, data collection and base mapping, geotechnical investigations and infrastructure supervision.

**Sitra Causeway, Bahrain**
- Total length: 400 m
- Main span: 60 m
- To be completed: 2009
- Client: Ministry of Works and Housing Road Projects and Maintenance Directorate Bahrain
- Services by COWI: Feasibility study including environmental aspects design of realigned highway, traffic management, preparation of tender documents and supervision of construction.

**Sungai Johor, Malaysia**
- Total length: 1,708 m
- Main span: Main span of 500 m and an approach girder with 48 m span
- To be completed: 2008
- Client: Ranhill Bersekutu Sdn. Bhd.
- Services by COWI: Concept design, basic and detailed design of superstructure incl. pylons and bearings, construction follow-up.
**Kuwait Causeway, Kuwait**
Total length: 1,228 m
Main span: 2 x 494 m
Client: Ministry of Public Works, Roads Administration, Kuwait

**Åwaitaine Bridge, France**
Total length: 1,767 m
Main span: 400 m
Completed: 2003
Client: Direction Départementale de l’Équipement (DDE) de la Gironde, Bordeaux
Services by COWI: Tender design for rehabilitation of main cables, tender evaluation and technical observation during the performance.

**2nd Bosphorus Bridge, Turkey**
Total length: 1,090 m
Main span: 1,090 m
Completed: 1988
Client: Freeman Fox & Partners, UK for the General Directorate of Highways, Turkey
Services by COWI: Structural adequacy check.

**Hålogaland, Norway**
Total length: 1,570 m
Main span: 1,345 m
To be completed: 2013
Client: COWI in Denmark (Dissing+Weitling), COWI in Norway (Johs. Holt)
Services by COWI: Follow-up during the construction phase.

**Malmö, Swing Bridge, Sweden**
Total length: 70 m
Main span: 25 m and a shorter back stay span of 15 m
Completed: 2004
Client: Municipality of Malmö
Services by COWI: Tender design, detailed design in Design & Builtphase.

**Råån Bridge, Sweden**
Total length: 254 m
Main span: 80 m
Completed: 2000
Client: The Swedish Rail Authorities, Banverket
Services by COWI: Conceptual design, detailed design, follow-up during construction.

**Aquitaine Bridge, France**
Total length: 1,767 m
Main span: 400 m
Completed: 2003
Client: Direction Départementale de l’Équipement (DDE) de la Gironde, Bordeaux
Services by COWI: Tender design for rehabilitation of main cables, tender evaluation and technical observation during the performance.

**Malta, Swing Bridge, Sweden**
Total length: 70 m
Main span: 25 m and a shorter back stay span of 15 m
Completed: 2004
Client: Municipality of Malmö
Services by COWI: Tender design, detailed design in Design & Builtphase.

**Kuwait Causeway, Kuwait**
Total length: 1,228 m
Main span: 2 x 494 m
Client: Ministry of Public Works, Roads Administration, Kuwait
Danube Clearance Project, Yugoslavia

COWI's assignment involved removing the remains of 3 large cable-supported bridges across the Danube river, which were destroyed when NATO bombed Yugoslavia in 1999.

Completed: 2005
Client: EU commission
Services by COWI: Planning, project engineering, preparation of tender document, tendering, contract management, supervision and preparation of final documentation after completion of the project.

Sheikh Zayed Bridge, Abu Dhabi, United Arab Emirates

Total length: 842 m
Main span: 234 m
Completed: 2005
Client: Works Department, Emirate of Abu Dhabi
Services by COWI: Independent design check.

Brygge Bridge, Copenhagen, Denmark

Total length: 190 m
Main span: 25 m and 44 m
Completed: 2006
Client: E. Pihl & Søn A/S
Services by COWI: Design of bridge construction.

Knippelsbro, Denmark

Total length: 140 m
Main span: 2 fixed spans both 44 m and a double-leaved steel span channel of 35 m
Completed: 1991
Client: Port of Copenhagen and Municipality of Copenhagen
Services by COWI: Conceptual design, detailed design and supervision of construction.

Aagade Pedestrian Bridge, Copenhagen

Total length: 65 m
To be completed: 2008
Client: Municipality of Copenhagen, Denmark
Services by COWI: Competition design, tender design, follow up design.

Vejle Fjord Bridge, Denmark

Total length: 1,710 m
Main span: 110 m
Completed: 1981
Client: Ministry of Public Works The Road Directorate
Services by COWI: Preliminary investigations, preliminary and tender design, detailed design and construction supervision.

Danube Clearance Project, Yugoslavia

COWI's assignment involved removing the remains of 3 large cable-supported bridges across the Danube river, which were destroyed when NATO bombed Yugoslavia in 1999.

Completed: 2005
Client: EU commission
Services by COWI: Planning, project engineering, preparation of tender document, tendering, contract management, supervision and preparation of final documentation after completion of the project.
Seo-Hae Grand Bridge, Korea
Total length: 7,400 m
Main span: 470 m
Completed: 2000
Client: Korean Highway Corporation
Services by COWI: Construction supervision and training.

Viaduc du Chavanon, France
Total length: 330 m
Main span: 300 m
Completed: 2000
Client: Scetauroute, France
Services by COWI: Design review and ad-hoc construction engineering assistance.

YongJong Grand Bridge, Korea
Total length: 4,400 m
Main span: 300 m
Completed: 2002
Client: Samsung Engineering and Construction Company Ltd.
Services by COWI: Design check of detailed design of suspension bridge superstructure, conceptual design for dehumidification system.

Naini/Allahabad Bridge, India
Total length: 1,600 m
Main span: 260 m
Completed: 2004
Client: The Ministry of Surface Transport (MOST), India and National Highways Authority of India (NHAI)
Services by COWI: Feasibility study, detailed design and construction supervision.

2nd bridge across the Panama Canal
Total length: 1,050 m
Main span: 420 m
Vertical clearance: approx. 80 m
Completed: 2004
Client: Ministry of Public works (MOP), Panama
Services by COWI: Project management, design review and site inspection.

Ålvsborg Bridge, Gothenburg, Sweden
Total length: 930 m
Main span: 418 m
Services completed: 2007
Client: Vägverket, Gothenburg, Sweden
Services by COWI: Condition assessment of suspension hangers and planning for further inspection and rehabilitation works.

Älvsborg Bridge, Gothenburg, Sweden
Total length: 930 m
Main span: 418 m
Services completed: 2007
Client: Vägverket, Gothenburg, Sweden
Services by COWI: Condition assessment of suspension hangers and planning for further inspection and rehabilitation works.
Nelson Mandela Bridge, South Africa
Total length: 284 m
Main span: 176 m
Completed: 2003
Client: SANRAL (south African National Roads Agency Limited, department of transport)
Services by COWI: Conceptual design, tender design, tender assistance, detailed design, ad-hoc assistance during construction.

2nd Orinoco Bridge, Venezuela
Total length: 3,120 m
Main span: 300 m
Completed: 2005
Client: Constructora Norberto Odebrecht S.A.
Services by COWI: Independent design review of the cable-stayed main bridge, independent design review of the superstructure for the approach bridge and ad-hoc assistance to the contractor during construction of the bridge.

Zárate-Brazo Largo Bridges, Argentina
Total length: 15,000 m
Main span: 330 m
Completed: 1977
Client: Dirección Nacional de Vialidad, Argentina
Services by COWI: Inspection, testing and rehabilitation design.

Qatar – Bahrain Causeway
Total length: 42,000 m
Main spans: 250 m
Client: Ministry of Municipal Affairs and Agriculture, Qatar

Gibraltar Strait Crossing, Spain – Morocco
Total length: 14 km or 27 km
Main spans: 2 x 5,000 m or 3 x 3,500 m
Client: SECEGSA, Madrid, Spain and Société Nationale d'Etudes du Détroit, Rabat, Morocco.
Services by COWI: Pier concepts, ship protection systems, superstructure designs and preliminary design (~ 1995).
Architect: Dissing+Weitling.

Årsta Bridge, Sweden
Total length: 880 m
Main span: 78 m
Completed: 2005
Client: Banverket, Stockholm
Services by COWI: Tender and detailed design.