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Evolution of suspension bridges

Evolución de los puentes colgantes

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ABSTRACT

The suspension of bridges by cables is one of the oldest methods used for spanning relatively long distances with no intermediate supports. Though utterly simple in its basic concept, this system offers excellent opportunities for even very long spans.

The paper describes the evolution from medium span suspension bridges with relatively simple technology towards increasingly more sophisticated technologies, which lead to modern suspension bridges comprising many new innovations, such as continuous aerodynamic bridge decks, internal corrosion protection by dehumidification, using wind flow improving devices, wind screening, deflection control via hydraulic damping and buffer devices, wear reduction systems at bearings and expansion joints and the analysis of anchorage structures with detailed consideration of the soil/structure interaction.

The paper covers the most significant worldwide examples while focusing particularly on several Danish bridges of this typology and how the examination of previous experiences resulted in multiple design optimizations.

Future developments, which would allow extreme spans in the 3- 5 000 m range that are suitable for the Messina and Gibraltar straits, are also presented. This includes a review of the potential of innovative technologies such as new materials and aerodynamically driven active control systems.

KEYWORDS: Suspension Bridge, box girder, contrapeso, flutter, dehumidification unit.

RESUMEN

La suspensión de puentes por cables es uno de los métodos más antiguos para salvar vanos de longitud considerable sin soportes intermedios. Aunque es muy simple en su concepto básico, este sistema ofrece excelentes oportunidades incluso para vanos muy largos.

El artículo describe la evolución de los puentes colgantes de longitud media con tecnología simple, pasando por tecnologías más y más sofisticadas hasta llegar al puente colgante moderno que incluye muchas innovaciones como el tablero aerodinámico continuo y protección contra la corrosión interna mediante deshumidificación con dispositivos de mejora del flujo del viento, cribado del viento sin efectos adversos sobre la estabilidad aerodinámica, dispositivos hidráulicos de amortiguación para el control de la deformación y la reducción del desgaste de las juntas de dilatación y los rodamientos, así como estructuras de anclaje avanzadas, teniendo debidamente en cuenta la interacción suelo/estructura.

El presente artículo abarca los más significativos ejemplos en el mundo enfocándose en particular en varios puentes daneses de esta tipología y en cómo el análisis de experiencias previas llevó a optimizaciones en el diseño.

Desarrollo futuro con revisión del potencial de nuevos materiales como las fibras de carbono y otras nuevas tecnologías con sistemas de control activo aerodinámicos, permitirían tramos extremos de 3- 5 000 m adecuados para el estrecho de Messina y el estrecho de Gibraltar.

PALABRAS CLAVE: Puente colgante, sección cajón, anchor block, flameo, sistema de deshumificación.

1.
INTRODUCTION

Suspension bridges are one of the oldest solutions for spans exceeding by far those attainable with simple beam structures. They are based on one of the simplest structural systems ever devised, namely a rope suspended between elevated supports and anchored to some form of structure founded on the ground. The first suspended structures based on this principle

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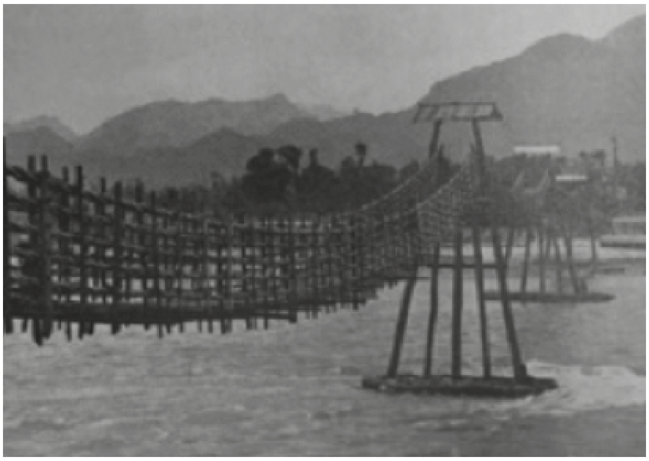


Figure 1. Bamboo Suspension Bridge - Min River - China.

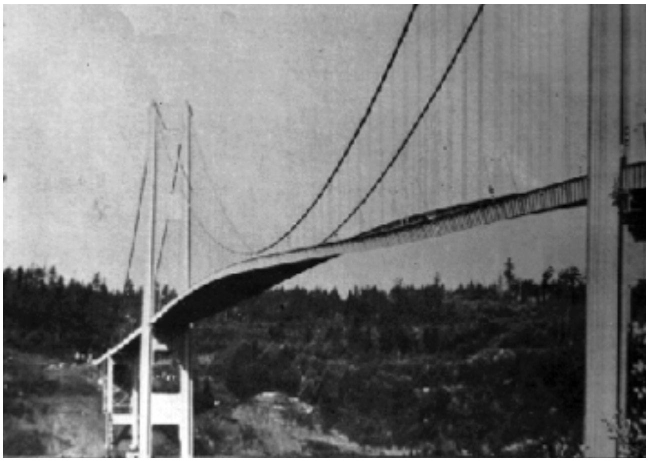


Figure 2. Tacoma Narrows Bridge - Washington State, USA.

are know from China, where ropes were crafted with twisted lianas. Bamboo fibers were later used in China, Tibet, Japan India and South America.

The Chinese, pioneers in the construction of suspension bridges, used iron chains for this purpose already before 600 AD. At the time, the deck was generally placed directly over the main cables and followed the chain suspension lines of those.

Later came the suspension of the deck from the main cables via clamped hangers.

The first major suspension bridges of rational design appeared some 200 years ago. The suspension bridge concept has since then undergone a steady and continuous development eventually reaching the longest spans in the world, with even much greater spans envisaged for the future.

While other structural systems like cable stayed bridges have also evolved with spans increasing over the years, the original suspension concept remains unsurpassed as the most suitable and economically feasible support concept for very long spans of up to 3 000 m, for the Messina Bridge, and even up to 5 000 m, as envisaged for a bridge on fixed foundations across the Strait of Gibraltar.

New materials, like carbon fibers with their much higher strength/weight ratio, will open the doors for even lighter and longer spans, which may consequently then call for active stabilization systems for adequate aerodynamic stability.

The article will present some of the major evolutionary steps in the suspension bridge technology which have contributed to longer and longer spans, with some indications of further possibilities for development into super long spans with new advanced materials and technologies.

2.

PAST DEVELOPMENTS

As it is generally the case, bridge engineers have always strived for reaching longer and longer spans, in a constant endeavor to beat records. Sometimes in this process, size effects inevitably become critical.

This was the case on the first Tacoma Bridge near Seattle, with a span of 854 m. On a November day, only four months after its inauguration in 1940 and under moderate wind speed conditions, the bridge exhibited large torsional oscillations. These resulted eventually in deformations and accelerations which caused the total collapse of the span.

Earlier suspension bridges, like the iconic Golden Gate Bridge in San Francisco completed only 3 years earlier, had all comprised a stiffening girder in the form of a truss system with large inherent stiffness and a quite acceptable aerodynamic behavior, albeit not optimum in terms of wind resistance.

For the Tacoma bridge, the truss concept was replaced by a slender plate girder with very high slenderness compared to the bridge span, which resulted in a section with practically no torsional stiffness and very poor aerodynamical properties. Thus, the collapse was caused by aerodynamical instability called "flutter" at moderate wind speeds.

One can only speculate if this accident could have been prevented had the designers consulted the Boeing aircraft designers, located in the same neighborhood, as they certainly were very familiar with the problem of flutter which has catastrophic consequences for aircrafts.

The accident obviously set back the development of suspension bridge for some years, until it was determined that it could be avoided by providing adequate torsional stiffness compared to the deck vertical stiffness, and with the improved shaping of the girder for better aerodynamic performance.

Even the earlier Golden Gate Bridge suffered from oscillations in the first part of its life, until torsional stiffness of the trussed girder was increased with the addition of adequate bracing at the lower chord level.

The Golden Gate Suspension span, directed by J.B. Strauss, set new standards for long span bridges with its 1280 m span, a clear record at the time.

The bridge employed tall riveted steel towers acting as a huge cantilevered Vierendeel trusses with no cross bracing from ground up and the girder was one of the slenderest at the time.

The sag ratio for the main cables is relatively high at approx. 1/8 with corresponding tall pylons, which contributes to the iconic gracious shape of the bridge with its iconic overall proportions.

Figure 3. Golden Gate Bridge, San Francisco, USA.

Undoubtedly, the Golden Gate Bridge stood as the finest example of the art of long span bridge engineering for a very long time and is still one of the most successful suspension bridges of all times also because of its scenic location.

The much later Verazzano Narrows Bridge in New York is with its 1 298 m span only marginally longer than the Golden Gate and employs basically the same technology.

A technological leap in suspension bridge technology came with the 988 m span Severn Bridge project in UK. The British designers developed a single slender and rather aerodynamically shaped box girder design for this bridge, and they even utilized its closed shape for sailing the individual segments of the prefabricated girder as ships on the estuary of Severn during high tides.

Further, the designers introduced inclined hanger systems with the aim of providing a triangulated truss-like behavior of the girder, suspension cables and hanger system and thus increased stiffness for wind and traffic loads.

The inclined hangers have however later been replaced by conventional vertical hangers in connection with a major overhaul and strengthening of the bridge because of fatigue concerns.

The nineteen sixties gave rise to increased developments in suspension bridge technology.

While the Severn bridge was under development in the UK, the project for the Little Belt Bridge in Denmark was taking shape.

3.
MODERN SUSPENSION BRIDGE

A. The Little Belt Bridge, Denmark

The basis for this first modern suspension bridge in Scandinavia were extensive studies of the worldwide suspension bridge technology.

The historic Brooklyn Bridge in New York by J.A. Roebling, with 488 m main span, completed in 1,883 comprising the first application of parallel galvanized steel wires for its 4 main cables and the Golden Gate and Verrazano Narrow Bridges were of course among the bridges looked at.

In particular, the Tancarville Bridge across the Seine in France and many others were intensively studied – all with the aim of extracting the very best experiences from past designs in order to create a unique design combining best structural performance with optimum advantages for the Owner regard-

Figure 4. Verrazano Narrows Bridge, N.Y. USA.

Figure 5. The Little Belt Bridge, Denmark.

Figure 6. The aerodynamic box girder with wind deflectors.

ing design and construction, as well as operation, maintenance and aesthetics.

The most important advances of technology and innovations which resulted from this global research were:

I. Use of symmetrical, as opposed to asymmetrical air foils, aerodynamic steel box girders with wind deflectors (guide vanes) as a result of consultations with aeronautical engineers and aircraft designers.

The girder section was developed with special consideration for fabrication of box girder segments at a naval shipyard with similar technology. Furthermore, it was refined by extensive wind-tunnel testing for stability against divergence and flutter related oscillations for all relevant wind speeds. As the shape could not be optimized just for aerodynamics, because wind can blow from both sides and because the primary purpose of the girder is to carry traffic, the edges of the girder would comprise rather sharp and less aerodynamical bends between the flat deck and bottom surfaces and the aerodynamic noses/trailing edges. However, the resulting release of vortices was found to be greatly attenuated by adding wind-deflector plates to the top edges of the girder.

Such plates have later been used also for the rather bluff section of the cable stayed Saint Nazaire Bridge and Great Belt Bridge with excellent results.

The box girder was presented to the bidding consortia as an alternative to a more traditional truss-based girder in order to generate a basis for competitive bidding amongst the consortia and methods. The result was that the box girder design provided an approximately 20% lower cost than the truss, and thus was ultimately selected for construction as it also presented considerable operation and maintenance advantages for the Owner.

II. Introduction of dehumidification for internal corrosion protection of the box girder and the main cable anchorages.

The internal steel surface area of the girder, including stiffeners and cross bracings or diaphragms, amounts easily

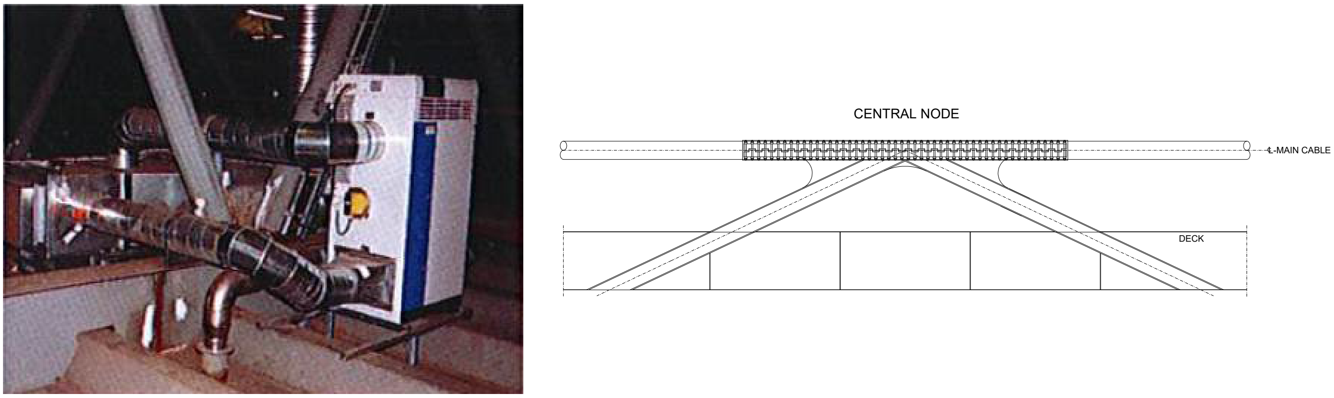


Figure 7. Central Node and dehumidification unit in box girder.

to more than 80% of the total steel surface area of the girder as the exterior is desired to be as slick and smooth as possible for aerodynamic reasons, and the riding surface is covered by mastic corrosion protection and pavement.

The principle of dehumidification for corrosion protection stems originally from the "moth-balling" of heavy military equipment and is based on the simple fact that steel does not corrode in atmospheres with relative humidity below 60%.

The advantages are multifold: The installation using standard off-the-shelf dehumidifier units and simple air circulation systems known from buildings can be accomplished at much lower costs than painting systems, and further the environmental and occupational safety concerns with internal painting is completely eliminated. As a bonus, dehumidification is even a much safer and more efficient method as the risk of quality deficiencies related to occasional nonpainted areas because of difficult access, and resulting localized corrosion, is also effectively eliminated.

Presently, dehumidification is considered the *de-facto* standard for corrosion protection of closed volumes in steel structures because of its proven efficiency and low cost of operation of the dehumidification units.

The concept has been further developed in Japan to comprise permanent corrosion protection of the main cables on existing bridges by means of circulating dehumidified air longitudinally in the cables taking advantage of the voids between the individual wires in the cable and using an airtight PE sheet wrapping on the cable.

III. Use of prefabricated twisted ropes as part-cables for the main cables instead of traditional spinning.
The standard for major suspension bridges was at the time the spinning of parallel galvanized approximately Ø5 mm wires between anchorage shoes arranged at both anchorage structures and subsequently wrapping of the wire bundles with a wire wrapping applied by a specialized purpose-designed machine.

In order to facilitate competitive pricing, the requests for pricing included both traditionally spun cables and prefabricated cables constituted by a number of parallel long lay twisted part cables –called "ropes"– which –after suspension by pulling over the catwalks as always used for suspension bridge construction– would be wrapped by a galvanized steel wire for assembly of the cable with a circular shape suitable for the cable clamps which in turn suspended the deck via the hangers. The bidding resulted in the prefab cable solution being selected for the Little Belt Bridge.

IV. Use of a central node connection between the main cables and the girder at mid-span for deflection reduction under asymmetrical loading.

The conventional suspension principle leads to relative longitudinal displacement between the main cables and the bridge deck. This means that shorter hangers will alternatively incline in either direction during passage of high concentrated loads like a heavy vehicle. This can cause fatigue on the short hangers, particularly at the anchorage sockets.

By fixation of the main cable to the deck at mid-span through the so-called central node, these relative movements are efficiently arrested and the vertical deflections as a result significantly reduced.

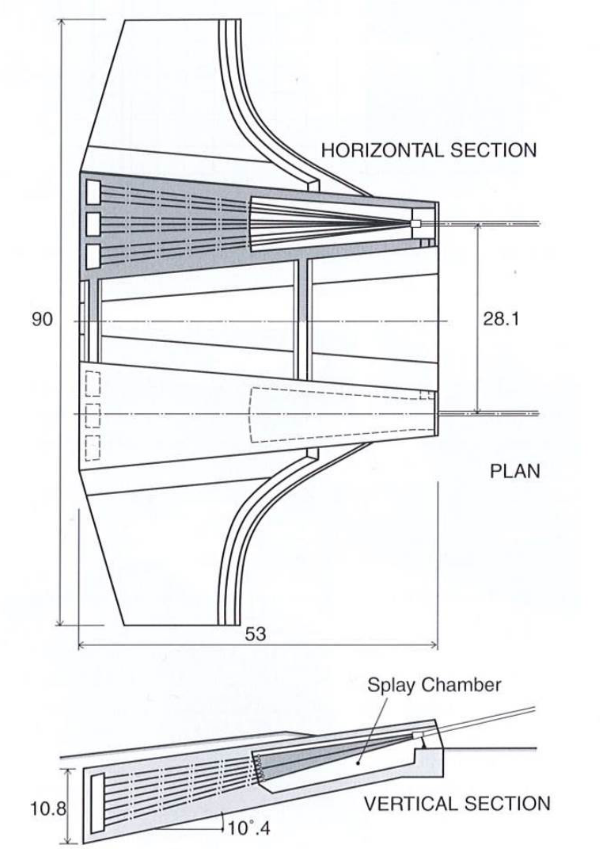
Therefore, this principle was adopted for the Little Belt Bridge and other later bridges.

V. Development of a unique underground anchorage slab structure for the main cables suitable for the fractured Little Belt Clay with adverse soil characteristics and with aesthetic advantages.

The Little Belt bridge is within in a zone with a geology of fractured fat clay. This over-consolidated fat clay is characterized by its susceptibility to slippery fractures and consequently the concerns over the shear strength at these fractures, which is highly un-predictable, make the design of anchorage structures under horizontal forces, which are typical for suspension bridges, critical.

The unique solution developed involved balancing the essential part of the horizontal component by an inclined 1.0 m thick underground anchorage slab ballasted with soil so as to generate by friction enough capacity to resist the live-load related anchorage forces, whereas the dead loads component of cable forces in combination with the self-weight of the anchorage plate and ballast soil is perpendicular to the underside of the large surface anchorage slab.

In addition, the deck over the dehumidified anchorage chambers, where the main cables separate into vulnerable



individual ropes, was particularly investigated for potential aircraft crashes and thus also –almost prophetical– for terrorist attacks.

An aesthetical side benefit of this unusual concept is that the anchor structures are completely buried in the side slopes of the Little Belt and thus nearly not visible and not disturbing the light elegant appearance of the bridge.

VI. Development of a special concrete mix design for the pylons with low cement content, low heat of hydration and excellent durability.

As the pylons along with the main cables essentially are non-replaceable for a major suspension bridge without the total disassembly of the whole structure, a meticulous research was carried out to develop very durable concrete for the piers and pylons. In this endeavor, attention was paid so as to minimize cracking in the massive structures by using of minimum cement content and thus generating minimum heat of hydration. This was achieved by the adequate selection of aggregate sources with optimum gradation.

VII. Pioneering design of main pylon piers with regard to risk for ship collisions based on systematic probabilistic approach.

As the main piers for the pylons are in the Little Belt water, investigation was made to safeguard the bridge against catastrophic ship collisions. This has resulted in the world's first systematic research of causes for ship collisions based on statistical data and the ship/pier interaction forces in the event of a collision.

Figure 8. Little Belt Buried Anchorage slab structure.

As ship collisions later have unfortunately become more frequent – some with very tragic outcomes with many casualties – the probabilistic methodology developed has proven very beneficial for the adequate analysis and decision making for later bridges.

The methods having been published in various technical papers are now universally used for major bridges crossing navigable waterways.

VIII. Involvement of an architect for assisting with the overall shaping of the bridge components to in the best possible way to fit into the hilly landscape with its gentle light curved and yet springy light nature of the bridge.

The Little Belt Bridge – although with a modest span of 600 m measured with today's eyes – set at the time of its inauguration in 1970 a new standard for modern suspension bridges which has subsequently been the basis for further development of much larger bridges.

B. The Great Belt Bridges in Denmark, 1977-78 proposals

The final decision to construct the Great Belt Bridge in 1976 provided an excellent opportunity to continue the development of the suspension bridge technology from the basis created for the Little Belt Bridge, but this time for much longer spans and heavier loads.

The design was to be for a 6-lane motorway and a dual track heavy duty railway to be carried on a bridge crossing over the international waterway of the Great Belt with some of the world's biggest ships and tankers..

After extensive studies of alternative solutions with due consideration of risks and consequences of ship collisions in the Great Belt, it was concluded that a minimum main span of 780 m was required. This was considered the maximum conceivable at the time for cable stayed, a world record for cable stayed span with a double track railway. However, a longer span was desirable so as to minimize the risk of collisions, which led to consider a long suspension span as the only feasible solution. The inherent flexible nature of suspension spans was a potential concern for railways because of their heavy loads and strict requirements for deflections and restricted allowance for angular alignment and profile changes at expansion joints.

Figure 9. Great Belt rail cum motorway bridge design 1,416 m span.

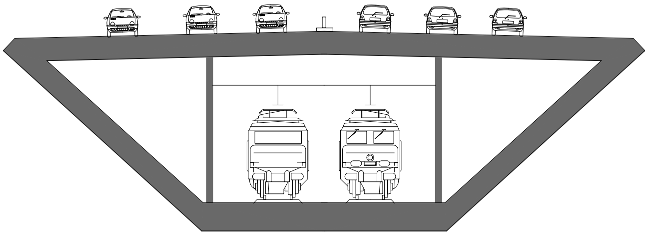


Figure 10. Double deck Bridge girder.

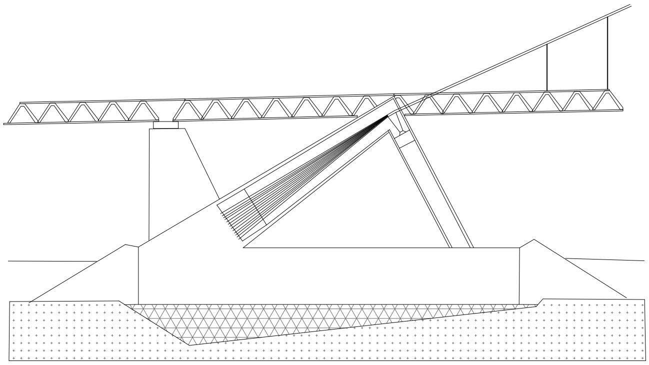


Figure 11. Anchor block structure for 1416 m main span.

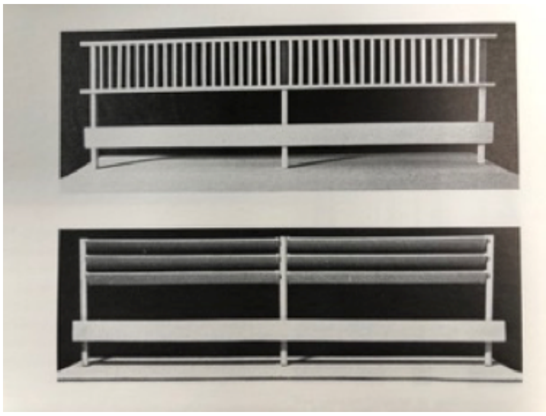


Figure 12. Wind screen concepts with excellent aerodynamic properties.

The continued studies concluded that a relatively long and heavy suspension span would actually generate a corresponding very desirable high main cable force which would be advantageous for sustaining relatively high concentrated train loads with reasonable deflections, and thus it was determined that a 1416 m double deck suspension span with dual railway tracks on the lower deck and 6 a lane motorway on upper deck would be feasible and meet railway stiffness criteria. This was found feasible because rotations at expansion joints could be controlled by using a partially fixed girder at the anchorages.

Building on the experience from the design and construction of the Little Belt Bridge the continued development of the suspension bridge suitable for heavy train loads comprised the following:

I. A 1416 m main span suspension bridge with relatively short side spans for increased stiffness.

The studies of spans from 1200 m up to 1800 m indicated that short spans would be too flexible for heavy loads and the stiffening girder would be easily overstressed because of inadequate main cable force. Conversely, very long spans –although leading to much higher main cable forces and dead load– were not found economical.

Thus, the selected 1416 m span was a reasonable technical and economical optimum which provided adequate lateral ship navigation clearances and overall cable/girder system stiffness for concentrated train loads.

II. A continuous double-deck girder from anchorage to anchorage with semi-fixity at the anchorages and with inclined triangulated trusses with closed box members connecting the 2 decks. All box members dehumidified for corrosion protection.

Contrary to previous suspension bridges at the time, which comprised expansion joints at the pylons – it was found advantageous to let the girder float continuously through the pylon structures suspended only by the hangers and thus avoiding hard points and the complications of expansion devices for the rail with associated angular rotations and maintenance issues.

Furthermore, the anchorage structure, conveniently shaped with a massive counterweight pier at the rear end, Figure 11 provided a convenient support possibility for the girder in addition to the support at the front of the anchorage structure. The relatively short distance between these supports provided an elastic fixity of the girder and thereby assured very small relative angular rotations at the expansion joints which would be acceptable even for high speed trains.

III. In order to further increase stiffness for short term loads like train passages, the bridge would include a central node as the Little Belt Bridge and huge hydraulic lock-up devices at the anchorages which would allow slow temperature variation generated movements, whereas the girder would be virtually fixed for short term passing train loads and

Figure 13. Great belt Suspension Bridge - 1,624 m main span.

thus reduce short term deflections.

IV. For the long span, aerodynamic stability was a concern, as was wind exposure to vehicular traffic on the high-level bridge, which needed a vertical clearance of min. 65 m for international shipping in the Great Belt.

It was known that ordinary wind barriers would create undesirable turbulence and lead to instability and/or buffeting of the bridge for relative low wind speeds.

However, extensive wind tunnel tests revealed that a barrier shaped so as to allow free flow of wind below the barrier and equipped with a semi-open barrier up higher acting like a huge wind resistor (reducing wind speed) would not only ensure stability as without barrier, but in reality, increase the aerodynamic stability of the bridge deck. In addition, such a barrier would be much more effective in reducing the overturning wind loads on high light vehicles because the wind forces would be reduced at a higher level. The effect is well known from aerodynamics of airplane wings using small turbulence generators.

V. In an attempt to minimize the visual impact of the colossal anchorages, the structure was designed as optimum fit for purpose by a triangulated tension and compression leg supported on a sand filled caisson to be placed by the floating off shore method similar to the Ekofisk platform in the North Sea. For balancing the loads for central loading at the underside of the anchorage, a sand filled counterweight pier was provided at the rear end of the anchorage.

The Great Belt Project was developed ready for construction in 1978, when the 2nd energy/economic crisis struck, and the project was shelved for another 8 years.

C. *The Great Belt Bridge 1992 -1998*

The Great Belt Bridge project was relaunched in June 1986 and this time with a requirement for a separate railway tunnel and 4 lane motorway bridge instead of the previous rail cum road bridge for 1978.

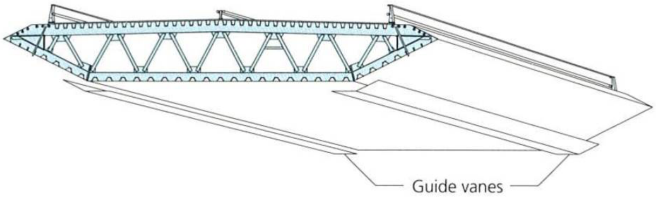


Figure 14. Great Belt Bridge girder with wind guide vanes.

Again, several studies for selection of the most appropriate solution were performed. The selection criteria was based on extensive studies of spans vs price comparisons with due regard to the need for compensating excavations in the sea bottom for the water flow blocking effect of the piers in the belt as well as through ship impact risk assessment by probabilistic analysis, statistics, theoretical and psychological navigation behavior of captains, as well as real time simulations in a new navigation simulation facility.

The end result of the extensive studies was the selection of a 1624 m main span solution for the East Bridge of the Great Belt as the solution which best satisfied all criteria.

The selected solution brought the suspension bridge technology another step forward:

I. Longest span continuous box girder length in the world with its approx. 2700 m continuity without expansion joints.

The box girder is continuously suspended between anchorages, where huge expansion devices with capacity of +/- 1 m expansion capability are located. The configuration of the box girder is developed for industrial fabrication in a shipyard with even more production-oriented details than the Little Belt Bridge and of course corrosion protection of the internal volume by dehumidification.

In order to assure adequate stability of the rather sharp-edged girder it was necessary to install wind deflector

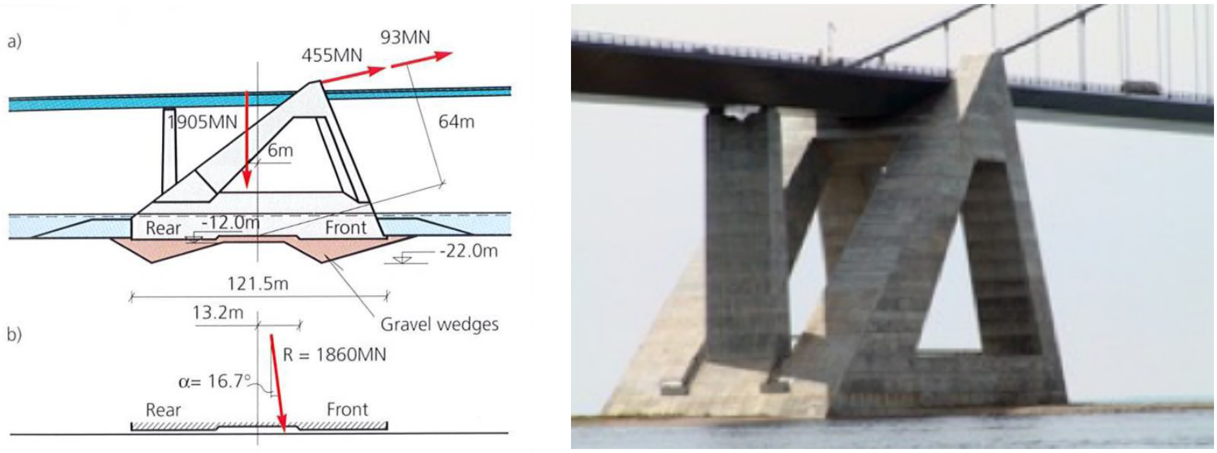


Figure 15. Anchor Block Structure - 1624 m main suspension span.

plates at the soffit to guide the wind flow around the corners between the horizontal soffit and the inclined sides of the box girder.

II. In order to limit deflections and improve aerodynamic stability, the bridge comprises, as Little Belt, a node connection of the main cables with the deck at mid-span through longitudinal fixation. Furthermore, huge hydraulic buffers were installed at the anchorages as developed already in 1977 in order to prevent longitudinal movements of the girders for short term loads passing the bridge, whilst at the same time permit long term slow expansion and contraction of the bridge deck caused by temperature variation. This system has reduced the accumulated movements of bearings and expansion joints to a very small fraction of the movements which would have taken place without such devices and thus wear and tear is reduced by several orders of magnitude.

III. The main cables, comprising 18 648 Ø 5.38 mm galvanized wires, were spun by an advanced accelerated spinning method using 4 spinning wheels. This allowed spinning the complete cables with 8 wires per spinning passage in only 4 months. This was again the result of putting prefabricated parallel wire strands PPWS in competition with conventional spinning at the time of tender.

IV. The 255 m tall concrete pylons were designed for ship impacts, on deterministic basis, of even the biggest oil tankers, 250000 dwt ships at 16 knots, because of their proximity to the main navigation channel.

The usual cross beam below the bridge deck, which would inhibit the clear view of the free-floating suspended girder through the pylon, was in collaboration with the architects moved to an optimum mid-height position on the pylons and thus provides for the light appearance of the deck through the pylons with no visual disruption of the elegant lines of the sleek girder.

V. The configuration of the anchorages was inspired on the 1978 solution in order to create a simple and open structure with minimal visual obstruction as a triangulated structure supported on a sand ballasted caisson built in dry dock and floated to the site and ballasted to sit on the previously prepared sea floor with inclined gravel pads – also inspired by the Little Belt anchorage structure configuration.

VI. All piers, including the main piers for the pylons, the anchorages and the approach span piers were built on shore for lowest cost and floated to the site for installation using the now common off-shore technique.

4.
FUTURE DEVELOPMENTS

It is expected that bridges in the future at certain locations will require longer spans, in the range of 3000 m and even up to 5000 m.

Studies have been made for the Messina Bridge for more than half a century. The span currently envisaged is 3300 m for a bridge comprising a double track railway and a six lane motorway. It will be one of the most challenging bridge projects ever with almost 400 m tall pylons and a huge span located in a known earthquake prone zone. However, the suspension bridge concept is well suited for earthquakes because its natural frequencies are very low and far from typical earthquakes frequencies, and thus the structures are not susceptible for large accelerations apart from those parts close to the foundations.

A detailed design has been developed ready for construction as and when decided.

The UN as well as the Spanish and Moroccan governments have shown interest in investigating the technical feasibility of a fixed link across the Strait of Gibraltar at several occasions.

This has led to the development of technically feasible, albeit not financially, bridge schemes on two different alignments across the very deep and geologically complex Gibraltar Strait.

The shallowest is a 28 km long alignment taking advantage of a saddle-like bathymetry with the possibility of

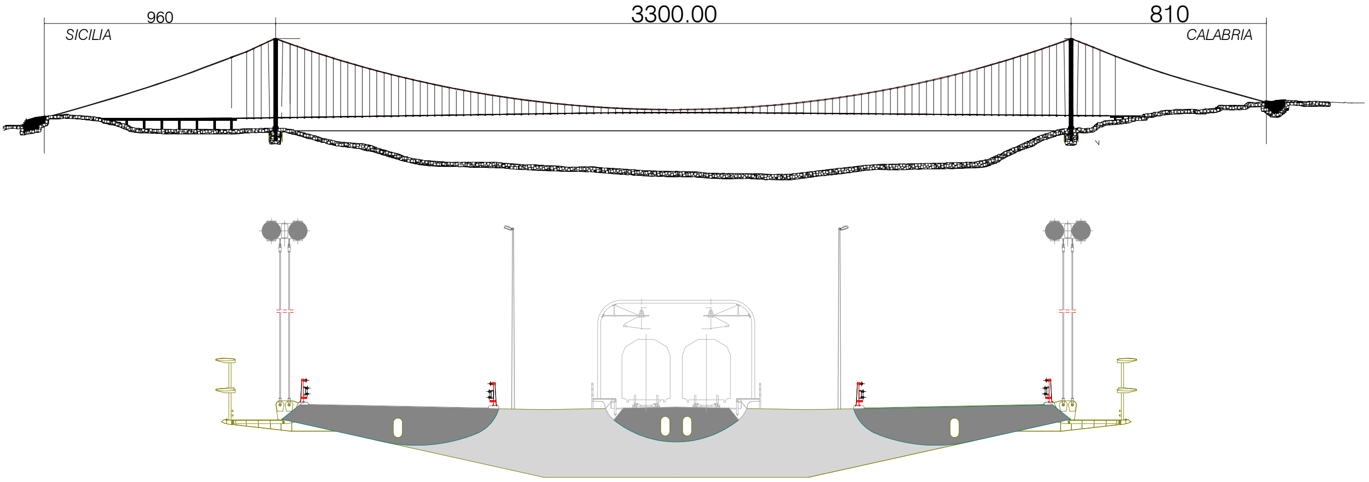


Figure 16. Messina bridge 3300 m span road cum rail bridge.

Figure 17. Gibraltar Strait - 3 x 3500 m suspension bridge solution.

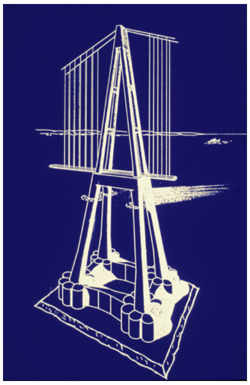


Figure 18. Off shore type bridge pier concept for 300 m water depth.

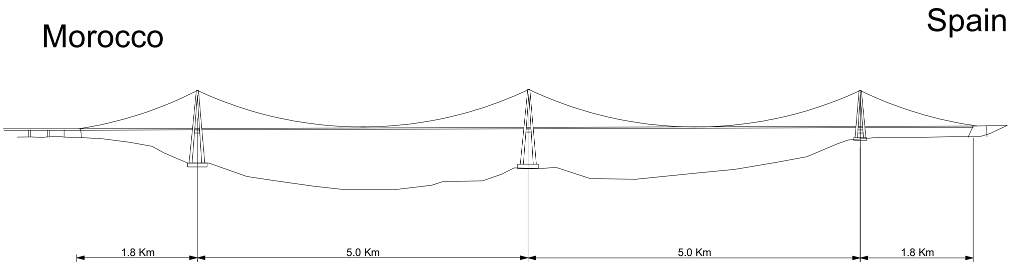


Figure 19. Gibraltar Strait 2 x 5000 m span solution.

placing off-shore type piers on water depths of 300 m approximately, which is similar to the deepest existing off shore oil and gas platform (Troll in the North Atlantic Sea). This concept would require 3 consecutive 3500 m spans using A-shaped pylons for rigidity.

A solution of much shorter length of 14 km has also been investigated, but water depth would dictate 2 consecutive 5000 m spans, and one center pier placed on approximately 450 m deep water.

A further serious complication is the risk of ship collisions and very difficult foundation conditions with chaotic geological strata and risks of earthquakes.

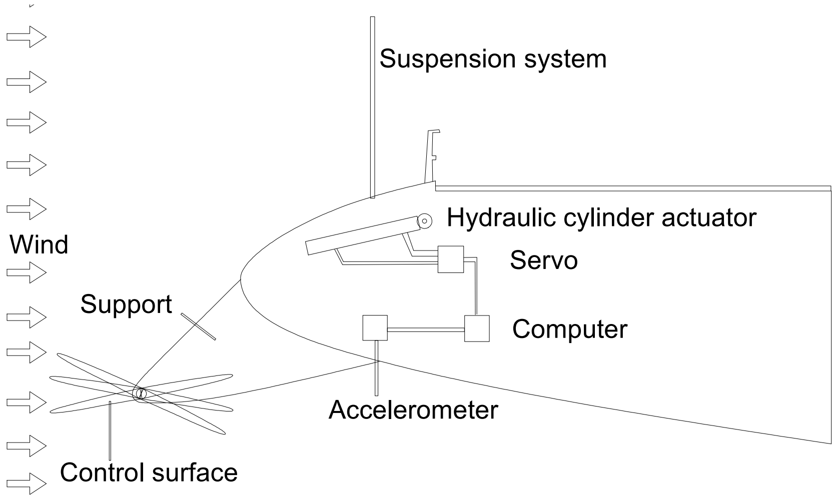


Figure 20. Active control system for aerodynamic stabilization of bridge decks.

The further development of such extreme bridges will require new considerations and the development of new technologies with materials of much improved strength/weight ratios like carbon fibers or similar.

These bridges will be lighter and use less material in the interest of saving on resources and cost as well as being environmentally friendly.

As a result of this development, it is inevitable that these bridges become more susceptible to aerodynamic instabilities, which can only be controlled by active systems.

Such a system, inspired by commonplace autopilots in airplanes, has been developed and patented as a suitable means for efficiently stabilizing bridge decks utilizing the destabilizing forces generated by the wind to also stabilize the bridge deck movements using actively controlled control surfaces as illustrated in the figures below.

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