SPANNING CENTURIES
A history of the modern suspension bridge
Suspension Bridges: past and present

Introduction
When Norway’s Hardanger suspension bridge opens next month it will have the 10th longest main span in the world. It will, however, be unique among its neighbours in the long-span record books because of its extreme slenderness (Figures 1 and 2). Norwegian bridge designers have a reputation for creating slender spans, which can be partially attributed to the country’s low traffic volumes and associated narrow bridge decks (Figure 3). Yet even by Norwegian standards this new bridge has a daringly narrow and shallow deck for such a colossal 1310m main span between towers. Indeed, with a deck width of only 18.3m the width-to-span ratio is just 1:72, significantly lower than that of any other existing suspension bridge. The other classic slenderness benchmark, depth-to-span, is almost as impressive at 1:403, although surpassed by a very few bridges in the Far East such as Yi Sun-sin at 1:507. The latter has a much wider deck compared with the Hardanger however, and could therefore be considered less slender overall (Figure 4).

These modern ultra-slender bridges are economical in terms of materials used, but ensuring they remain aerodynamically stable is challenging, especially in harsh environments such as exposed fjords. Suspension bridges have been chosen for many of the world’s longest spans on grounds of economy, uninterrupted air draft and bridgeable length, together with longevity and safety. The evolution of the modern suspension bridge has been characterised by epic struggles to achieve these aims. There have been many failures along the way, some of them spectacular; but progress continues. This article focuses on some of the iconic bridges (and the designers behind them) which paved the way to the creation of the modern suspension bridge.
James Finley: inventor of the modern suspension bridge

Born in Ireland in 1756, James Finley (accompanying his parents in a move to the US at some point prior to 1784) is widely acknowledged as having ‘invented’ the modern suspension bridge. A practicing judge and politician, Finley developed an interest in bridge design through his everyday involvement with community development issues.

His first, the Jacob’s Creek Bridge in Pennsylvania, was completed in 1801 and was fundamentally different from its primitive predecessors in two ways; the bridge deck was flat and it incorporated a degree of stiffness not previously achieved. Earlier suspension bridge decks followed the curvature of the main cables, and whilst some had used iron cables (e.g. the Winch Bridge, Middleton, England 1741), crucially these structures had no stiffening deck structure.

The Jacob’s Creek Bridge, with its 21m span, incorporated vertical hangers which supported the deck from the main cables which, in turn, were constructed from 1.25 inch square iron bars, wrought into chain links. The fundamental components of this early structure are still adopted for suspension bridge designs today and include anchorages, towers, main cables, hangers and a stiffened deck. In spite of taking out a patent on suspension bridge design, Finley’s bridges had detail flaws including under-specification of the cables. Several collapsed - some due to excess loading of snow or other unplanned loads. None survive today.

By the time of Finley’s death in 1828 at the age of 72, even his admired Jacob’s Creek Bridge had collapsed under the load of a horse-drawn carriage, a bitter blow for an early pioneer in the suspension bridge story.

Nevertheless, Finley’s pioneering work in suspension bridge design was not in vain. Captain Samuel Brown of the British Navy learned of Finley’s unique bridge form and built one of the first modern European suspension bridges, over the River Tweed on the English/Scottish border. So began the British chapter in the suspension bridge story.

Early British examples

Union

The Union Bridge, completed in 1820, had a main span of 140m and, with a width of 5.5m, was designed as a road bridge for use by carriages. Brown’s crucial innovation over Finley’s bridges was to replace the link chain cables with his own stronger invention; the eye-bar chain cable. These cables comprised lengths of flat or circular iron bars with bulbous ends containing a circular hole for connection with adjacent bars. Hangers to support the deck beneath were conveniently connected at the junctions between the eye-bar chains. Brown went on to produce several other notable suspension bridges; the most well known being the Brighton Chain Pier, with four spans of 78m, which (admittedly, in poor repair at the time) was later to collapse under oscillations caused by wind loading during a storm in December 1896.

Menai

The eye-bar chain cable was then used on the Menai Suspension Bridge, designed by Thomas Telford, which links the Welsh island of Anglesey to the mainland. With a main span of 176m it became the world’s longest suspension bridge when it was completed (Figure 5 and Table 1). Interestingly, around this time, durability considerations for materials were in debate...
as humorously portrayed in a work by Lewis Carroll:

“I heard him then, for I had just
Completed my design,
To keep the Menai Bridge from rust
By boiling it in wine.”

Clifton

This much admired bridge, perched high
above the Avon gorge, linking Bristol with
North Somerset, was completed in 1864
and is a Grade 1 listed structure with a main
span length of 214m (Figure 6). The bridge
incorporates several key developments in
design including wrought iron eye-bar chain
(Figure 7) which was an improvement on
earlier traditional link chain cables (although
it would be one of the last eye-bar chain
suspension bridges built anywhere in the
world). Other features are masonry towers
typical of the period (although in this case,
architecturally ornate with an Egyptian
style) and vertical hangers of iron bar from
the main cables to the deck. Roller saddles
carry the six chain cables over the top of
the towers to the anchorages. The bridge
was drawn by a young Isambard Kingdom
Brunel in 1831 for a design competition, but
he would not live to see the completion of his
greatest work. Interestingly Brunel ignored
the advice of his engineer father Marc
Brunel, who pressed his son to incorporate a
central pier, thinking the span too great.
The Menai and Clifton Bridges survive to
this day but, despite the high status of the
engineers involved, both structures suff
ered
from poor understanding of some of the main
principles of design; notably the lack of a
sufficiently stiffened deck. With their relatively
short spans, this was not to be a cause of
catastrophic failure for these bridges. The
Menai suff
ered from the effects of wind, as
the Brighton Chain Pier and Finley’s bridges
had done before it, but did not completely
collapse, although the timber deck was
repaired on numerous occasions. The Clifton
bridge was also known to oscillate under
wind loading. There was a general defi
cency
in theory, such that when Telford designed
the Menai he ignored the current thinking
and made an apparatus to determine key
components through experiment.

The US

Brooklyn: a family affair

Perhaps the greatest bridge building story
of all time is that of the Brooklyn, an epic
tale of perseverance amidst family tragedy,
of brilliance and ingenuity, which concludes
with the completion of one of the world’s
most beautiful and original structures.
(Figure 8). A masterpiece of early American
design, the bridge had an unprecedented

Table 1: Record suspension bridge spans

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Location</th>
<th>Year completed</th>
<th>Main span (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Union</td>
<td>UK</td>
<td>1820</td>
<td>140</td>
</tr>
<tr>
<td>Menai</td>
<td>UK</td>
<td>1826</td>
<td>176</td>
</tr>
<tr>
<td>Fribourg</td>
<td>France</td>
<td>1834</td>
<td>266</td>
</tr>
<tr>
<td>Wheeling</td>
<td>USA</td>
<td>1849</td>
<td>308</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>USA</td>
<td>1867</td>
<td>322</td>
</tr>
<tr>
<td>Clifton (Niagara Falls)</td>
<td>USA</td>
<td>1869</td>
<td>386</td>
</tr>
<tr>
<td>Brooklyn</td>
<td>USA</td>
<td>1883</td>
<td>486</td>
</tr>
<tr>
<td>Williamsburg</td>
<td>USA</td>
<td>1903</td>
<td>489.5</td>
</tr>
<tr>
<td>Bear Mountain</td>
<td>USA</td>
<td>1924</td>
<td>497</td>
</tr>
<tr>
<td>Delaware River</td>
<td>USA</td>
<td>1926</td>
<td>533</td>
</tr>
<tr>
<td>Ambassador</td>
<td>USA</td>
<td>1929</td>
<td>564</td>
</tr>
<tr>
<td>George Washington</td>
<td>USA</td>
<td>1931</td>
<td>1067</td>
</tr>
<tr>
<td>Golden Gate</td>
<td>USA</td>
<td>1937</td>
<td>1280</td>
</tr>
<tr>
<td>Verrazano Narrows</td>
<td>USA</td>
<td>1964</td>
<td>1298</td>
</tr>
<tr>
<td>Humber</td>
<td>UK</td>
<td>1981</td>
<td>1410</td>
</tr>
<tr>
<td>Akashi Kaikyo</td>
<td>Japan</td>
<td>1998</td>
<td>1991</td>
</tr>
</tbody>
</table>
enormous caissons. These allowed workers to excavate the bed of the river using compressed air, forcing the caissons to sink deeper until solid bedrock was met. Tragedy struck the Roebling family again when Washington suffered a severe attack of decompression sickness (‘the bends’), while fighting a fire deep inside one of the caissons. Although lucky to be alive, he was partially paralysed, unable to write, and would never again visit the bridge construction site.

The Brooklyn baton then passed to Washington’s wife. Emily Roebling acted as an intermediary between her bedbound husband and the construction site. Managing the project off-site was no easy task, especially considering that a bridge of this scale and complexity had never been attempted. But the Roeblings persevered, unrelentingly fighting the New York Bridge Company when substandard steel wire was supplied for the main cables. This was replaced at the supplier’s own cost. Further complications included the late addition of 1000t of extra steelwork to the deck trusses to support a railway.

When the bridge was opened in 1883, it had taken more than 13 years to build and cost at least 20 lives, but it proved a turning point in the development of suspension bridge engineering. This bridge set the stage for steel wire cable, still used today, and marked the end of the era for heavy masonry towers.

**The French connection**

The steel wire cables of the Brooklyn had their ancestry in the early work of the French brothers Marc and Camille Seguin who had realised the inherent weakness of eye-bar cables: that they could literally only be as strong as their weakest link.
They developed instead the iron wire cable, and so began an era of French suspension bridge construction. The Pont de Tournon (1824) over the River Rhone comprised two main cables, each consisting of 112 wires of 3mm diameter. The cables proved to be successful and were used for the next 140 years. This success led to a boom in French bridge building, with approximately 200 suspension bridges being built between 1830 and 1850 – 10 times the number constructed in either the US or Britain.

The French style of suspension bridge at this time comprised multiple spans, with main cables anchored to the foundations of the large masonry towers, rather than using separate anchor blocks. The French engineer Vicat then contributed a further important innovation. He understood that prefabricated cables made up of numerous wires would (because wires were not able to move relative to one another) result in different stresses throughout the cross section, especially where cables were bent through large angles at the top of the towers. The Seguin brothers had also realised this, and used temporary towers to construct their cables so that the wires could be stressed equally. Vicat took this technique one step further by suggesting that the individual wires could be built up into cables in situ using the actual bridge towers. The principles of this aerial spinning technique are still used today.

The French boom ended around 1850 with the collapse of a number of bridges. The most tragic of these was the collapse of the Basse Chaine Bridge in Angers which failed under resonance of marching soldiers, with 226 fatalities. It would appear that the problems of inadequate bridge stiffness had yet to be fully understood (e.g. flawed theories of Navier who thought that mass alone ensured stability without need for stiffness). Few French bridges survive from this period. Indeed, some of these early lightweight suspension bridges even featured signs saying “Do not walk in step on the suspension bridge”, due to the problems of resonance. A related phenomenon would earn London’s Millennium Bridge its ‘Wobbly Bridge’ status 150 years later.

Charles Ellet, son of a Pennsylvanian farmer, studied engineering in France during the 1840’s boom, and brought wire cable suspension bridge technology back to America. His Wheeling Bridge spanning the Ohio River had an impressive 308m span, and took the record as the longest suspension bridge in the world. Unfortunately, Ellet mirrored the French style of lightweight un-stiffened bridges and the Wheeling blew down in a gale in 1854, just five years after its completion.

John Roebling set about to reconstruct the Wheeling Bridge, and through this he began his apprenticeship for the Brooklyn. He appreciated the need for increased stiffness in suspension bridge design and successfully reinstated the Wheeling with diagonal cable stays spanning between deck and tower, and a much stiffer deck; modifications which have stood the test of time. He continued his career with the design of several bridges, including the Ohio Bridge, before being appointed to the Brooklyn.

Roebling had designed the Brooklyn with stays from the towers to the deck similar to today’s cable stayed bridges, in addition to suspension cables and a partly stiff deck. He constructed the bridge empirically as he disregarded the theorems of the day postulated by Rankine and others. Nonetheless, the Brooklyn Bridge would play an important role in the development of the Deflection Theory which became the benchmark for all long-span designs in the 20th Century. John Roebling was a brilliant and successful engineer who developed tried and tested ideas from experience and painstaking observation, including an understanding of the reasons for the collapse of bridges such as the original Wheeling Bridge. His successors would try to add more theory to his empirical approach.

**Legacy of the Brooklyn and start of a golden era**

A young engineer who had studied civil engineering in New York’s Columbia University, Leon Moisseiff, was very interested to learn of the failure of a number of hangers in the main span of the Brooklyn Bridge in 1901, which resulted in its temporary closure. Moisseiff rediscovered and validated a theorem published by Melan in 1888 called ‘The More Accurate Method’, and renamed it ‘The Deflection Theory’. This replaced the older, less accurate ‘Elastic Theory’ which ignored deflections in the cables caused by live loads.

Although some of the lessons of the success of the Brooklyn were learned, a putative lack of understanding of the significant design features of the Brooklyn then led to a variety of designs in the US. The Williamsburg Bridge, just north of the Brooklyn, had already been designed using the elastic theory, perhaps the only long-span suspension bridge to be designed this way. It would become the world’s longest main span at 489.5m, but use of the obsolete theory made it one of the bulkiest suspension bridges ever constructed and it quickly gained a reputation for looking cumbersome and ungainly. Its 12.2m deep truss deck resulted in a 1:40 depth-to-span ratio, although chief designer Buck would be the first to build such a bridge entirely from steel.

The next major span, the Manhattan Bridge, completed in 1909 just east of the Brooklyn on the East River, was the first to be developed using Deflection Theory (Figure 9). With a Warren truss of just 8.2m depth for a 450m main span, it represented a more economical design and marked a great success for Moisseiff and Deflection Theory.

A golden era of long-span bridge building began in the United States, with the Delaware and Ambassador Bridges completed in 1926 and 1929, their main spans of 533m and 564m respectively being the first to exceed 500m. Yet it was the George Washington Bridge that really pushed the boundaries with its huge 1067m main span across the Hudson River, which doubled the main span record when it opened in 1931.
George Washington

Lead engineer Othmar Ammann had appointed Moisseiff as a technical advisor for the superstructure, and together they produced designs for a two-tiered truss deck of total depth 8.8m. However, only the upper 4m deep deck was initially built (the second deck was added 31 years later), creating a very slender and relatively un-stiffened span. Crucially, the bridge's stability was reliant on its significant mass, which is reflected in the size of the four main cables (each 914mm in diameter) and massive steel towers which weighed 18,600t each. Originally it was intended that these towers would be clad with masonry, but the Great Depression and a shortage of money would preserve the striking skeletal towers we see today (Figure 10).

Golden Gate

The George Washington Bridge would hold the longest span record for six years until 1937, when San Francisco would steal the limelight from New York City. Construction of the famous Golden Gate Bridge began in 1933 at roughly the same time as the San Francisco-Oakland Bay Bridge. With its 1280m main span across the Golden Gate and its orange art deco towers, styled by local architect Irving Morrow, it has become one of the most recognisable structures ever built. Its shallow trussed deck and 227m tall towers were constructed without setback once the problematic pier foundations had been completed. Joseph Strauss was well aware of the slender nature of his creation, as was Moisseiff, but believed the 910mm diameter main cables were sufficiently large to stiffen the structure. However in ferocious storms the bridge was susceptible to vertical and sometimes even torsional vibrations, and had to be stiffened in 1953 through the addition of lateral bracing between the bottom chords of the trusses. Yet the drive for increasing slenderness and economy would continue until 1940, when a spectacular bridge collapse would abruptly change the course of long-span bridge design.

Tacoma Narrows

With some of Americas largest bridges relying on mass alone for stability in high winds, the lesson of the need for deck stiffness perceived by Roebling was perhaps not fully appreciated, and this, coupled with the use of a novel type of deck girder, led to a most spectacular failure.

Plate girders had been used for short span suspension bridges in Germany and other European countries since the early 1900s, but their introduction to long-span bridge design in America in the 1930s was to prove disastrous. Back in New York, Ammann's 701m main span Bronx-Whitestone Bridge was hailed as the most delicate and slender suspension bridge built to date when it opened in 1939, with its 3.3m deep plate girder and depth-to-span ratio of 1:209 (Figure 11). Aesthetics and economy were clearly at the forefront of the designer's mind when he conceived his bridge, and he readily acknowledged that the dead weight per metre run was 2.5 times less than that of the George Washington Bridge, the latter a semi-flexible structure known to be stable because of its mass.

Yet Moisseiff took the plate girder one step further with his Tacoma Narrows Bridge, for he conceived a 2.4m deep plate girder for the world’s third longest main span at 853m (depth-to-span ratio of 1:350). Crucially, the bridge deck was very narrow as it was only required to support two lanes due to low traffic volumes, and thus it was longer, narrower and shallower than the Bronx-Whitestone Bridge. Open truss type decks, through which the wind could travel, had been replaced with the bluff bodied surfaces of the plate girder.

In November 1940, just four months after inauguration, the main span of the Tacoma Narrows Bridge became subject to large torsional vibrations under a modest 42mph wind speed and ultimately collapsed. Vortices generated at the edges of the plate girder, around which the wind had to flow, helped produce torsional oscillations which were of divergent amplitude. During its four month life, the bridge had been known to suffer from vertical vibrations, which earned it the nickname 'Galloping Gertie', but this torsional mode had not before been witnessed. The narrow lightweight deck had insufficient mass and torsional stiffness, all factors which contributed to a bridge that was aerodynamically unstable. Experts on
the board of inquiry who were appointed to investigate the failure, led by Amman, cleared Moisseiff’s name stating that “The collapse resulted from actions and forces previously ignored or known to be unimportant that became dominant in the new range of magnitude and proportions of this exceptional bridge”. Yet Moisseiff’s career was over, and he died less than three years later.

Attention turned to other slender bridges of similar construction, including the Thousand Islands, Deer Isle and, in particular, the Bronx-Whitestone. Vertical deflections of 35cm had been detected in the latter, and although much smaller than those observed on Tacoma, were still cause for concern. Diagonal stay cables were installed between tower tops and plate girders in December 1940. Further action was taken in 1946 when a 4.3m high Warren truss was connected to the top of the plate girders, which spoiled the clean lines of the bridge (Figure 12), but still mass dampers were needed in 1988. More recently in 2003, the heavy trusses were removed to restore the bridge to its original form and reduce dead load on the deck, relieving the main cables. Stability has been ensured through the addition of lightweight FRP V-shaped fairings, mounted onto the outside of the plate girders, around which the wind flows smoothly.

Learning from failure: new approaches
Following the Tacoma collapse, suspension bridge design changed course. Design in America eventually focused on two types:

- the ‘aerodynamic truss’ approach e.g. Mackinac Bridge (known locally as the Big Mac); which has stiffening trusses, a road deck which acts as an aerofoil, and open grids in the bridge centre allowing upward air flow and a relatively light, economical construction
- the ‘stability through mass’ approach e.g. the Verrazano Narrows Bridge; the heaviest suspension bridge ever built, modelled on the George Washington

Birth of the Box Girder
British long-span designs, led by the Severn and Forth Road Bridges and followed by the record-breaking Humber, differed from their US counterparts, with the emphasis placed on the post-war drive for economically efficient design.

The Forth Road Bridge was completed in September 1964. Its designers, Freeman Fox & Partners (superstructure) and Mott, Hay & Anderson (substructure), succeeded in producing an economical bridge. The 156m tall diagonally braced high tensile steel towers were the centrepiece of material savings, and weighing just 2450t each, were 70% of the weight of typical American examples. Such savings were realised through the use of welded steel box construction, with each tower leg comprising just five plated cells, contrasting sharply with the multi-cellular riveted designs typical of some of the American spans. Further savings were implemented through the use of a steel orthotropic deck plate over the 1008m main span, supported on top of the 8.4m deep by 23.7m wide truss. The lighter main span allowed savings to be translated into the hangers, main cables, towers and anchorages.

However, even the innovations introduced in the Forth could not match events that were about to unfold at the Severn Estuary. Designed by the same team, the 8.4m deep truss earmarked for the Severn Bridge (Figure 13) was reduced to just 4.3m by considering composite action between the orthotropic deck plate and truss beneath. Further evolution of the deck continued during extensive wind tunnel testing at Thurleigh, until Gilbert Roberts of Freeman Fox & Partners tested a scale model of a streamlined trapezoidal box girder made from plywood. Although the box girder was not a new invention, it would be the first time that it was incorporated into a long-span suspension bridge, and it offered significant advantages over traditional truss type decks. Being of closed cross section, the box girder has a high torsional resistance, and its streamlined profile allows air to move around rather than through it, helping to eliminate any destabilising vortices. With a depth of only 3m, the revolutionary Severn box girder deck was an all-welded construction, which further reduced the weight of steel required. In addition, the 18m long and 118t closed box girder segments were buoyant, and could therefore be floated out into the Severn.
were constructed from just a single stiffened cell (Figure 14). With a weight of 1090t per tower, these would be some of the lightest ever constructed for a long-span bridge (compare these with the 18,600t towers of the George Washington Bridge). The Severn represented a real breakthrough for suspension bridge design worldwide when it opened in 1966, and set the stage for the next generation of record breaking spans. Gilbert Roberts earned a knighthood for his work, yet less than a decade later there were concerns about the bridge.

So progressive was the fully welded box girder design that engineers could not be sure how much damping, if any, would be provided and so had opted to incline the hangers in order to increase stiffness. Use of non-vertical hangers was novel, and it was later concluded that they acted rather like the diagonal members of a truss, experiencing stress reversals which were responsible for the fatigue problems that followed (and had been predicted by Dr Tadaki Kawada\(^2\)). All 340 hangers were ultimately replaced with those of larger diameter in 1987. The slender, ultra lightweight towers were also strengthened, by building new towers internally to relieve vertical load, though such works were partly required to cope with a huge increase in traffic loading. There is debate that the bridge lacks sufficient mass to prevent some of the oscillations which lead to fatigue. Despite construction of the cable stayed Second Severn Crossing, the original bridge still remains an important link between England and Wales. With its depth-to-span ratio of 1:324, it approaches what Moisseiff had hoped to achieve aesthetically with his slender plate girders over the Tacoma Narrows some 27 years earlier.

Ironically, more than a century before the Severn Bridge, the Britannia railway bridge over the Menai Strait got very close to the box girder suspension concept. However, the engineer Robert Stephenson, son of famous railway engineer George Stephenson of ‘Rocket’ fame, made the box sections so big (large enough for the railway to run inside the box) that he eventually dispensed altogether with the planned suspension cables.

**Legacy of the Severn**
The Freeman Fox box girder, introduced across the Severn, became popular in the next wave of suspension bridge designs in the 1970s and 1980s. Turkey’s First Bosphorus Bridge, an intercontinental crossing which quickly became congested due to high traffic demand, featured a 33.4m wide box girder for its 1074m main span. Designed by Freeman Fox & Partners, this bridge also featured diagonal hangers (for the problems of the Severn had not yet been identified by the time it was completed in 1973).

The Humber Bridge would also be designed by the same British consultancy, with the revolutionary aerodynamic box girder concept facilitating a record-breaking 1410m main span which was opened to traffic in June 1981. Although inclined hangers were adopted in a similar fashion to the Severn and First Bosphorus Bridges, the towers were significantly different, being of reinforced concrete design. Slipforming was adopted by contractor John Howard & Company to construct the 159m high towers, which was a novel concept in bridge building and allowed for financial savings. However, any economic benefit was soon lost when complications arose forming the pier on the south side of the estuary; work was eventually completed a year behind schedule. With its unusual asymmetrical side spans of 280m and 530m on the Hessle and Barton sides respectively, resulting in a total suspended length of 2220m for its 4.5m deep deck, the design is an aesthetical and technical success.

Opened in 1988 to relieve its older neighbour, the Second Bosphorus Bridge (Fatih Sultan Mehmet Bridge) would feature a box girder deck that was 50% heavier than that used for the first crossing. With an almost identical main span of 1090m, this increase in weight could be partially attributed to new Turkish design loading which required the bridge to support 145t tanks, spaced end to end across the span. The additional mass of the box girder provided sufficient stiffness to the deck to render the problematic inclined hangers unnecessary, so traditional vertical suspenders were used. The Humber would be the last suspension bridge (of only three worldwide) to feature the inclined hangers.

**Bridge design today**
The Hardanger represents one current direction in design, built with features such as great slenderness, aerodynamic box section deck and aerial spinning of cables. However the current world record holder for the longest main span does not feature a box for its stiffening girder, rather a more traditional American open truss type deck, incorporating aerodynamic design along the lines of the Mackinac Bridge.

Completed in 1998, the Akashi Kaikyo...
Cable-stayed designs have been favored for the latest two British long-span bridges, with the replacement Firth of Forth crossing already under construction and the Mersey Gateway design well advanced. Have the main cable corrosion problems of the Severn, Forth and Humber bridges influenced the current trend in long-span designs in the UK? Dehumidification equipment has been retrofitted to the main cables of both Forth and Humber bridges, which has reduced the relative humidity within the cable voids to about 40%, thus preventing corrosion, and appears to be working well. Durability is clearly a priority research area for suspension bridge main cables, which unlike those of cabled stayed bridges, are not replaceable. The Hardanger cables have a 120 year design life, showing the progress made in this area since Finley’s earliest bridges.

Where uninterrupted navigation of waterways is required, for example Denmark’s Storebaelt Bridge and the proposed Bonny River Suspension Bridge in Nigeria, or for spanning deep water or gorges such as Norway’s Hardanger and even to some extent the Clifton, then suspension designs will always have a niche. It is unlikely we will see land based suspension bridges where intermediate piers can be constructed (such as the Millau Viaduct in France).

For ultra-long spans such as the proposed Strait of Messina Bridge with its 3300m main span, the paradox of mass still presents a real problem. Given the current tensile strength limits of the main cable

---

**Table 2: Suspension bridges ranked by longest main span (as of August 2013)**

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Bridge</th>
<th>Location</th>
<th>Main span (m)</th>
<th>Completion date</th>
<th>Deck type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Akashi Kaikyo</td>
<td>Japan</td>
<td>1991</td>
<td>1998</td>
<td>Truss</td>
</tr>
<tr>
<td>2</td>
<td>Xihoumen</td>
<td>China</td>
<td>1650</td>
<td>2009</td>
<td>Twin-box</td>
</tr>
<tr>
<td>3</td>
<td>Great Belt East</td>
<td>Denmark</td>
<td>1624</td>
<td>1998</td>
<td>Box</td>
</tr>
<tr>
<td>4</td>
<td>Yi Sun-sin</td>
<td>South Korea</td>
<td>1545</td>
<td>2013</td>
<td>Twin-box</td>
</tr>
<tr>
<td>5</td>
<td>Runyang</td>
<td>China</td>
<td>1490</td>
<td>2005</td>
<td>Box</td>
</tr>
<tr>
<td>6</td>
<td>Nanjing Fourth Yangtze</td>
<td>China</td>
<td>1418</td>
<td>2013</td>
<td>Box</td>
</tr>
<tr>
<td>7</td>
<td>Humber</td>
<td>UK</td>
<td>1410</td>
<td>1981</td>
<td>Box</td>
</tr>
<tr>
<td>8</td>
<td>Jiangyin</td>
<td>China</td>
<td>1385</td>
<td>1999</td>
<td>Box</td>
</tr>
<tr>
<td>9</td>
<td>Tsing Ma</td>
<td>Hong Kong SAR</td>
<td>1377</td>
<td>1997</td>
<td>Box</td>
</tr>
<tr>
<td>10</td>
<td>Hardanger Fjord</td>
<td>Norway SAR</td>
<td>1310</td>
<td>2013</td>
<td>Box</td>
</tr>
</tbody>
</table>

**Conclusions**

Bridge carries six lanes of the Honshu-Shikoku Highway across the Akashi Strait in southern Japan (Figure 15). Originally intended to have a 1990m main span flanked by two equal 960m side spans, the Great Hanshin earthquake in January 1995 moved the towers further apart, increasing the main span to 1991m. To save weight, the stiffening truss of 35.5m wide by 14m deep is of all-welded construction, and features a steel orthotropic deck plate with open grating between highway lanes to increase aerodynamic stability. The 287m high diagonally braced steel towers are the tallest ever built, and support the two 1122mm diameter main cables, each comprising 290 strands. Due to the high probability of typhoons in the region, aerial spinning was deemed by engineers to be unsuitable. Instead, the main cables were prefabricated in strands of up to 100 individual wires with these strands being pulled into position to make up the cable. Cable dehumidification by forcing dry air into the interior spaces of the cables was also used to reduce corrosion (a method also used on the Hardanger), a far cry from boiling in wine! Preference for a truss type deck over a box girder can probably be explained by the rapid development of Japanese long-span bridges in the 1980s, a competency developed from studying American practice; the leading authority at the time. Ranked in order of longest main span in the world, the Akashi Kaikyo is the only bridge in the top ten which employs a truss, the other nine all featuring box girders (Table 2).
steel, it is understandable that engineers strive to minimise the weight of the deck, which leads to reduced stiffness. Increasing mass alone to ensure stability would not appear to be an economical solution, especially as the efficiency of longer spanning bridges decreases with a higher percentage of the main cable capacity being required to support its own weight. Perhaps Roebling was right all those years ago with the Brooklyn - which in effect is a hybrid cable stayed and suspension bridge. Loss of stiffness due to a reduction in mass could be reinstated through the addition of stay cables. It would appear that such an approach has been suggested for the third Bosphorus crossing.

Cables could become synthetic and lighter in future, although much research is needed. These lighter cables could span longer distances with reduced loading on towers and hangers. Synthetic cables could then theoretically be tapered towards the centre of the bridge to match the variation in tensile forces, reducing weight and loading. Decks could become partly or wholly composite material, with gains in stiffness and weight reduction.

Great progress has been made in the field of aerodynamics exemplified by the confidence of the Norwegians in their outstandingly slender bridges, with their latest designs incorporating guide vanes and vortex spoilers on the soffit of the box girders (Figure 17). Future very long spans could feature active aerodynamics, where wind speed and direction sensors along the bridge feed data to computers which adjust vanes or flaps along the deck edges, a little like the stabilizers on a ship reduce rolling and pitching.

We are clearly only part way through the fascinating story of suspension bridge design.

Acknowledgements
Jubilee Travelling Scholarship 2012/13 provided by the Lancashire & Cheshire Regional Group of The Institution of Structural Engineers; Department of Civil and Environmental Engineering, University of Surrey; Mr Peter Buckland, Principal, Buckland & Taylor; Mr Colin Howard, Senior Tutor in Civil Engineering, University of Surrey; Mr James Parsons, Partner, Cass Hayward; Mr Thomas McGonagle, Bridge Engineer, Cass Hayward; Statens Vegvesen, The Norwegian Public Roads Administration

References

Bibliography
Cruickshank D. (2010) Bridges: heroic designs that changed the world New York: Collins