STRUCTURAL SAFETY FROM AN INTERNATIONAL PERSPECTIVE

PAST, PRESENT AND FUTURE

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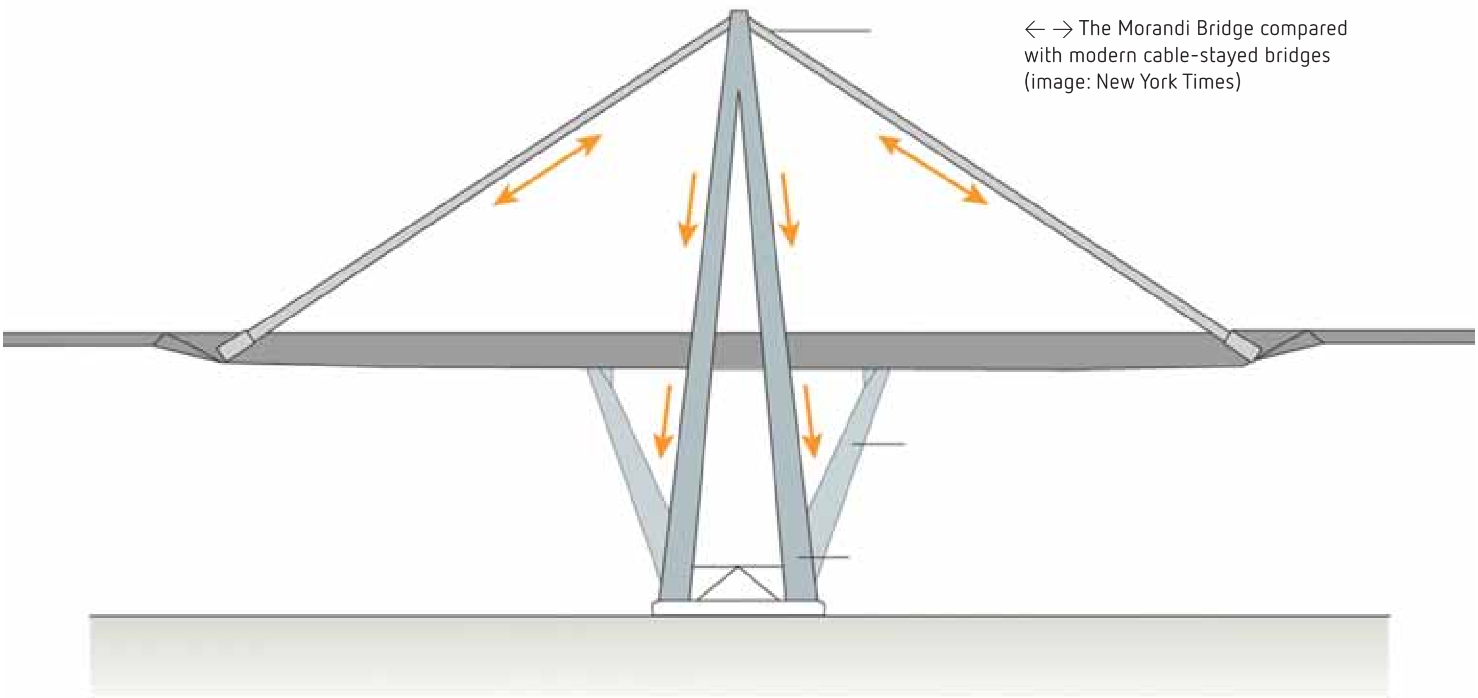
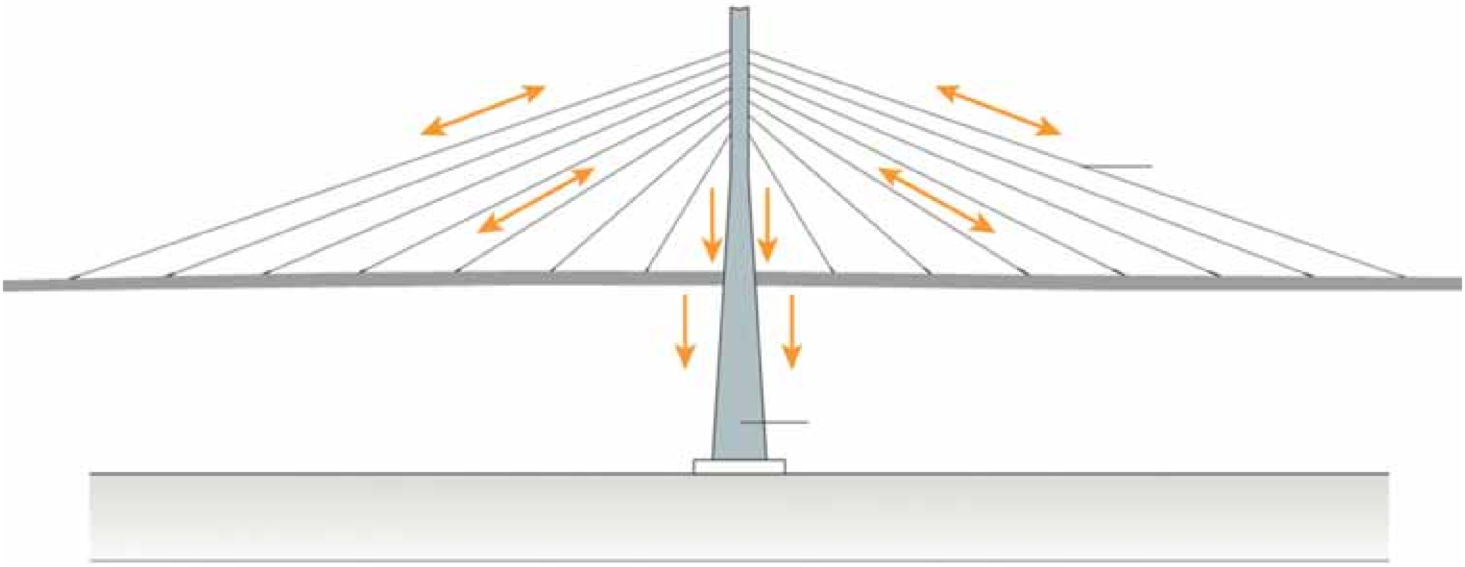


← → The Morandi Bridge compared with modern cable-stayed bridges (image: New York Times)

Collapsed Morandi Bridge in Genoa, Italy (image: New York Times)

Although the cause of the Morandi bridge collapse in Genoa, Italy, is not yet confirmed, lessons can already be learnt from this catastrophic event. On the back of "Genoa" and a near-miss in the UK, an international perspective on structural safety is illustrated with examples from the past, present and future.



The three bridges over the Firth of Forth (image: Scottish Construction Now)

MORANDI BRIDGE, GENOA, ITALY

The Polcevera Viaduct, otherwise known as the Morandi Bridge, named after its designer Riccardo Morandi, is a cabled stayed bridge completed in 1967. During a thunderstorm on the 14 August 2018, the bridge partially collapsed, killing 43 people, and leaving a huge gap in both the local community and Italy's strategic road network.

First of all, it must be stressed that the investigation into the cause of the collapse is ongoing and until the investigation is complete, it is only possible to speculate. Some possible reasons of the collapse (adverse weather, increase in traffic demand and age of the construction) have been identified immediately after the tragic event, but maintenance issues, general deterioration of the structural system and presence of corroded stays have also been highlighted by experts.

Morandi's bridge has been much admired by engineers and architects for its simplicity and clear expression of the load paths, but it subsequently created a lack of redundancy in the design. A second load path – the remaining stays to resist the additional load transfer from of a sudden failure of a stay – is not included in the design (see page 27).

The apparent lack of redundancy does place extra emphasis on the need for rigorous inspection and maintenance. However, inspection of the critical stay cables was made difficult by Morandi's use of prestressed concrete encasement.

Morandi innovated with the early use of pre-stressed concrete and cable-supported spans, but without knowing all about its impact on durability and robustness.

In the 1990s the eastern stays of the eastern most pier were strengthened after detected corrosion, likely due to marine chlorides (Mediterranean Sea) and from the application of road de-icing salt. Additional external steel cables were installed on the exterior of these concrete stays. However similar work was not carried out on the other two piers, including the one that collapsed.

Undertaken studies in Italy, France and Germany have brought to light that the general condition of European bridges, and especially those constructed after WWII, are in need of renovation or replacement due to corrosion and structural deterioration.

STRUCTURAL SAFETY OF BRIDGES IN THE UK

The Highway authorities in the UK undertake regular inspection of bridge structures and they place emphasis on durability and maintenance in their design standards. These measures have generally proved satisfactory

New design Morandi Bridge

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in maintain the UK's road infrastructure. At a local level, recent research by the RAC foundation has found approximately 3,500 local council-maintained road bridges to be substandard, representing 4,6% of the UK total. Many of these bridges have weight restrictions and are under programmes of increased monitoring.
Despite the relative health of bridges in the UK, there have been several high profile near-misses, demonstrating that the UK is not immune to the problems faced by bridge engineers worldwide. According to the New Civil Engineer, the UK have experiences five near-misses in the last 15 years, including the Forth Road Bridge spanning the Forth outside Edinburgh, Scotland.

Actually three world class bridges span the Forth within a few hundred meters of each other. Each bridge is built in a different century and demonstrates a different bridge engineering solution.

- **Forth Bridge** **Cantilever** **1890**
- **Forth Road Bridge** **Suspension** **1964**
- **Queensferry Crossing** **Cable Stayed** **2017**

These bridges provide an interesting array of examples of the issues around bridge maintenance and present an evolution in the attitude taken towards long term maintenance at the design stage of bridges.

THE FORTH BRIDGE

The Forth Bridge is a steel cantilever rail bridge designed by John Fowler and William Barlow, and constructed in 1890. It is the first major structure in the UK to be constructed from steel.
The principal maintenance issue has been the repainting of the large surface area of steelwork requiring a permanent maintenance team of painters. In 2002, work began to apply a new 3-coat paint system which is expected to last a minimum of 20 years. Since completion in 2011, and for the first time in its history, no permanent painters are employed on the bridge.
In many ways the bridge is an example of the 'build and forget' approach to bridge design. The bridge is inherently resilient due to its very robust construction, but at the high cost of the inefficient use of building material and an expensive and dangerous inspection and painting regime.

FORTH ROAD BRIDGE

The Forth Road Bridge is a long-span suspension bridge and was opened in 1964. At that time, the bridge had the fourth-longest main span in the world (1006 m). Its deck supports a dual two-lane carriageway and there is a separate footway/cycle track on either side. About 25 million vehicles now cross the bridge each year, more than twice the amount of traffic it was designed for.
In contrast to its heavy 19th century neighbour, the Forth Road Bridge presents an efficient lightweight structure.


The Forth Bridge (image: EG Focus)

Forth Road Bridge (image: http:// photoeverywhere.co.uk)

However aspects of the attitude of 'build and forget' was still present during its design, and within less than half of its original design life, the bridge began to show signs of significant deterioration.

One of the major issues to affect the bridge has been corrosion of the main suspension cables. Unfortunately, there is no other way (yet) to inspect the main bridge wires than to take the wrapping wire off and to open up the cables. In this respect the Forth Road Bridge bears similarity to the Morandi Bridge in Genoa.
In 2004 the Forth Road Bridge became the first suspension bridge in Europe to have its main cable opened up to check for signs of corrosion. Although the main cable showed no exterior signs of deterioration, the concern was that corrosion might be present inside – as had recently been discovered in the cables of American long span suspension bridges.

When the interior of the cable was inspected, engineers were surprised to find that 8-10% of the cable's strength had already been lost as a result of corrosion – despite the cable at that time being just 40 years old.
It was clear that action was required to try to halt or limit the deterioration. An acoustic

Internal inspection and broken wires (images: Engineer's Journal - Engineers Ireland)

monitoring system was installed in 2006 in order to monitor future wire breaks within both cables, and to provide information regarding the panels to be opened up for the next internal inspection.
Based on good experiences in Europe, but also Japan and the USA, the decision was taken to install a dehumidification system on the Forth Road Bridge with the aim of reducing the relative humidity to below 40% where corrosion cannot occur. The drying out process was completed by the end of 2009. The dehumidification has been successful and inspections to date suggest no further loss of

largest to feature cables which cross at mid-span. This innovative design provides extra strength and stiffness, allowing the towers and the deck to be more slender and elegant.

The bridge presents an evolution in the attitude towards long term maintenance in bridge design. From the outset the design has sought to integrate whole life maintenance, with considerations given to monitoring condition and behaviour and to facilitate the repair and replacement of components if required.

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Queensferry Crossing (image: Construction Enquirer)

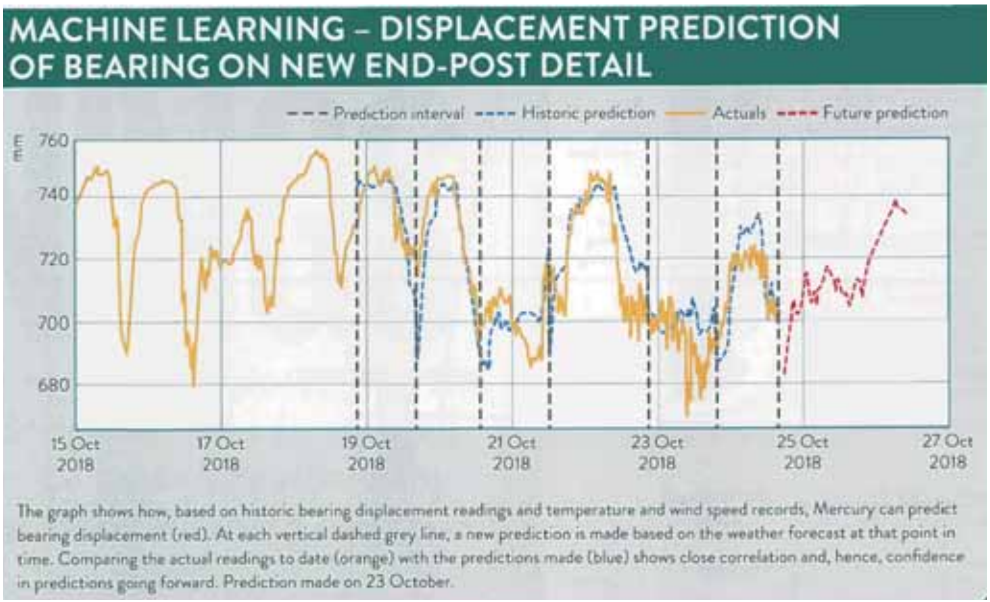
strength has occurred. The bridge is now expected to achieve its original 120 year design life.
However, due to the uncertainty and immanent risk of closure, in 2007 it was decided to construct a new road bridge – the Queensferry Crossing – to safeguard a vital road link for the Scottish economy.

QUEENSFERRY CROSSING

The Queensferry Crossing is a new cable stayed road bridge opened in 2017. The 2,7 km structure is the longest three-tower, cable-stayed bridge in the world and also the

The strands that make up the stay cables can be individually replaced without the need to restrict traffic on the bridge. The bridge has also been equipped with an advanced structural health monitoring system: about 1000 sensors have been installed to monitor the global behaviour of the bridge and its environment in real time (wind, temperature, corrosion, motion and any strains).
This allows the operator to respond quickly to extreme events, to target inspections and to carry out pre-emptive interventions to avoid potential failures.
Recently machine learning has been added to the software which will enable it to use historical data to identify trends or behaviours not yet recognised by the maintenance team. It will take time to collect data to make meaningful predictions, but it is expected that the software will be able to make predictions about what safety measures or repairs should be carried out in advance of forecasted severe weather events.

In addition to advanced monitoring systems, advances in technology are also been utilised to improve traditional visual inspections by engineers.



Machine learning leading to future predictions of behaviour (graph: New Civil Engineer)

A virtual reality (VR) model of the bridge has been created and the maintainers are trialling the use of VR by engineers to view 360° camera footage captured by drones on site. The use of such technology in bridge inspections is still new, but the Forth Road Bridge and the Queensferry Crossing are at the forefront of these developments in the UK. The latest technologies are helping to maintain the structural health of both bridges and allowing both to be brought into an integrated 'managed crossing scheme' safeguarding the future of this vital road link.

MAKING THE VISION VIABLE

BuroHappold Engineering designs bridges without disregarding future maintenance. The whole life approach to bridge design is key in each design, including the one for the Northern Spire in Sunderland.
Forming a major part of the regeneration of the North East, the Northern Spire - an imposing two span cable-stayed bridge with an A-frame pylon - is the first new road bridge in Sunderland for more than 45 years. Crossing the River Wear, it carries two lanes of traffic in each direction, together with dedicated cycle ways and footpaths, creating a much-needed safe passage for all modes of transport.

The Northern Spire is designed to minimise maintenance requirements and to facilitate ease of maintenance. All elements of the bridge are detailed to cater for future access requirements of a principal inspection. Key areas with regard to access are both the

The Northern Spire (image: BuroHappold Engineering)

adjustable and fixed end anchors locations at deck level and within the pylon respectively. The access has been fully integrated into the principle structure. Openings in structural members have been consider in the design and detailing of these along with all fixtures, fittings and clearances required for access. Besides facilitating access for inspection and maintenance, it has also been ensured that all inspection and testing equipment are catered for in the design and in the detailing of the bridge. Platforms, ladders, guardrails, internal lighting and power sources have all been provided. Connection points have been provided on the steel pylon for installation of a proprietary scaffolding system for access to the external pylon. The inner face of the pylon is to be accessed by abseiling.
Lessons have been learnt from the past and the below mentioned technical enhancements have been incorporated in the Northern Spire, and these could also be considered in future bridge designs as well:

- Cable strands individually replaceable.
- Dehumidifying system installed in internal steel pylon.
- Concrete pylon base has high strength concrete specified and the outer layer of reinforcement in stainless steel to minimise the need for future repair works.
- Ends of underdeck electrical service ducts are accessible from abutment galleries. Junction boxes and drawing pits accessible from opening in the bridge deck.
- Additional service ducts provided for possible future services.
- Carefully detailed sub-surface drainage integrated with kerb drainage units.
- Minimisation of number of bearings, including elimination of bearings at pylon location.
- No bearings located over water (nor therefore subject to direct salt water spray).
- Jacking points provided at all bearing locations.
- Added robustness and future-proofing provided by extra load and movement capacity of bearings.
- Highly durable elastomeric expansion joints which do not require replacement.

It is up to us, architects and engineers, to prevent disasters like in Genoa and near-misses like in Edinburgh, and to assure structural safety and breath-taking bridge design continues to walk hand in hand for generations to come.
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Deck to pylon access (image: BuroHappold Engineering)