PAST, PRESENT AND FUTURE: STRUCTURAL SAFETY FROM AN INTERNATIONAL PERSPECTIVE

BUROHAPPOLD ENGINEERING

14th March 2019

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MORANDI BRIDGE

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MORANDI BRIDGE BACKGROUND

- Genoa, Italy
- Cabled stayed bridge
- Designed by Riccardo Morandi
- Completed in 1967
- Vital link in Italy's road network

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MORANDI BRIDGE BACKGROUND

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- Cabled stayed bridge
- Designed by Riccardo Morandi
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Disaster struck on 14th August 2018 killing 43 people

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MORANDI BRIDGE STRUCTURAL FAILURE

- Lack of redundancy in the structural design
- Adverse weather conditions
- Increase in traffic demand
- Age of construction
- General deterioration of structural system
- Presence of corroded stays

Progressive collapse took only 4-5 seconds according to CCTV

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MORANDI BRIDGE
LACK OF REDUNDANCY

- Very simple stay arrangements, using prestressed concrete stays rather than the steel cables already in wide use at the time
- Need for rigorous inspection and maintenance (difficult by concrete encasement)
- Admiration by engineers and architects for its simplicity clear expression of the flow of forces
- Modern cable stay structures use multiple stay cables and are typically designed for the accidental loss of one or more stays

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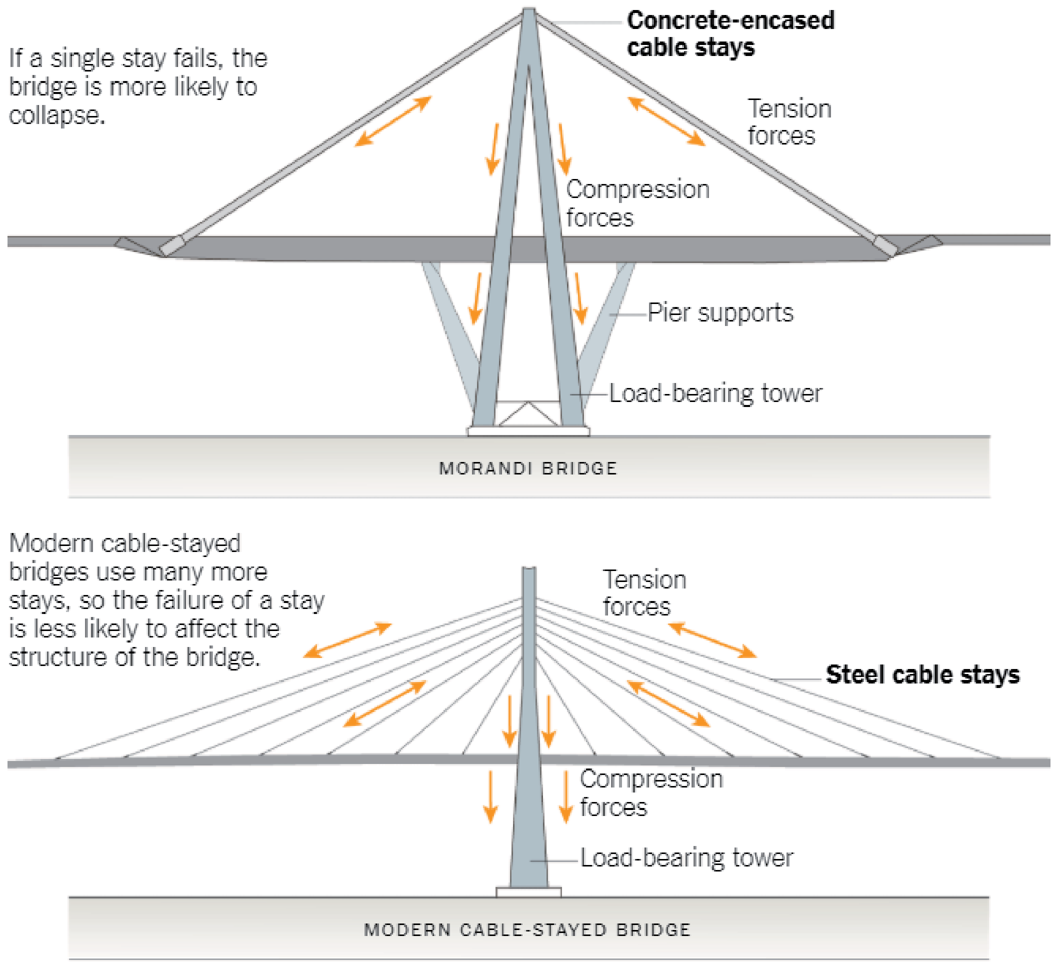
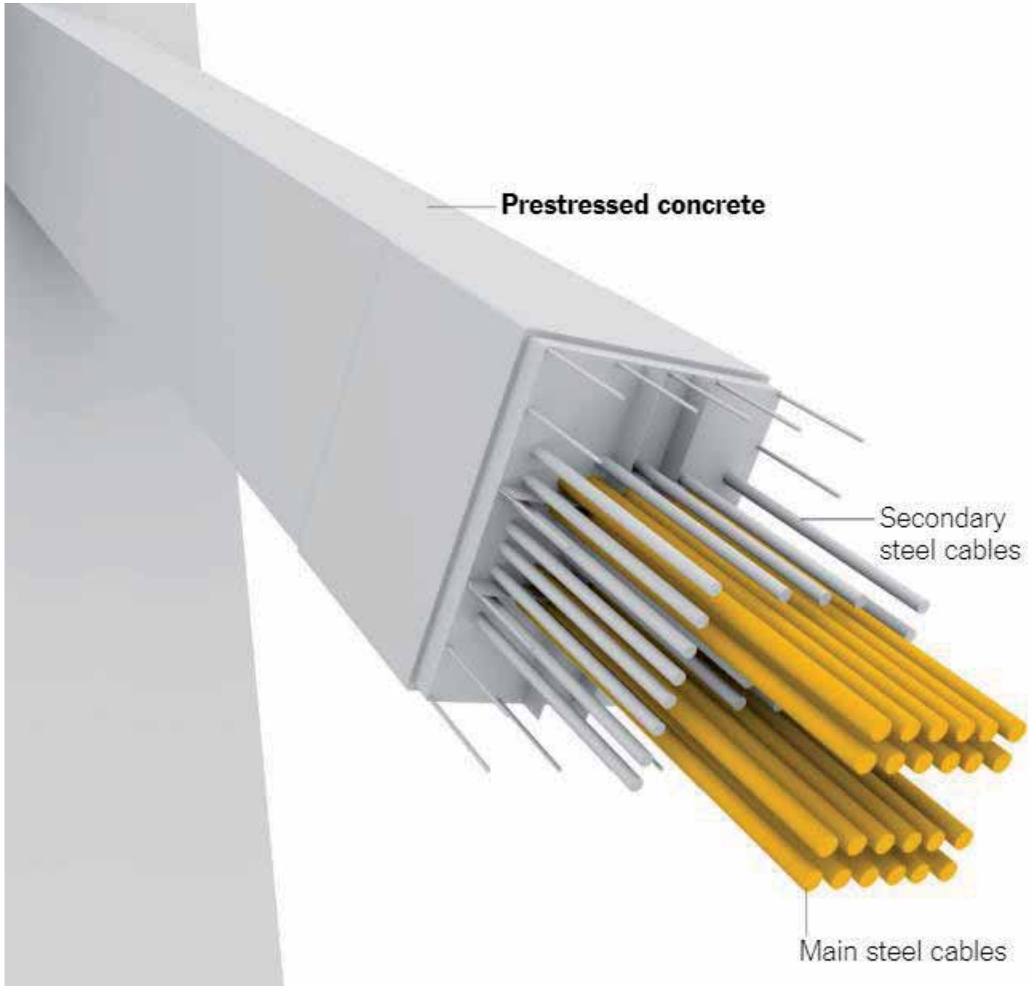


MORANDI BRIDGE
LACK OF PROVISION FOR INSPECTION AND MAINTENANCE

- Learning cycle of pre-stressed concrete and cable-supported spans: durability and robustness
- Italy, Europe, USA, and Canada: suffering from corrosion of reinforcement and/or pre-stressing tendons
- Key problem is the difficulty in inspecting the encased steelwork
- Aggressive environment for the durability of steel (chlorides and de-icing salts)



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MORANDI BRIDGE EARLY WARNINGS

- Eastern most pier was strengthened after corrosion and other problems were discovered in 1990s
- Additional external steel cables were installed on the exterior of the concrete stays
- Similar work was not carried out on the other two piers, including the one that collapsed
- Modal analysis pointed to possible corrosion in the stays of the collapsed pier
- Recommended monitoring and further investigation were never acted upon

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MORANDI BRIDGE
AFTERMATH OF THE COLLAPSE (I)

- Significant number of bridges are in need of renovation or replacement due to corrosion and structural deterioration
- Many RC bridges built after WWII are reaching the end of the typical lifespan
- Significant financial investment in managing the decline is required
- Design of modern structures should be durable to minimise future maintenance burden

MORANDI BRIDGE
AFTERMATH OF THE COLLAPSE (II)

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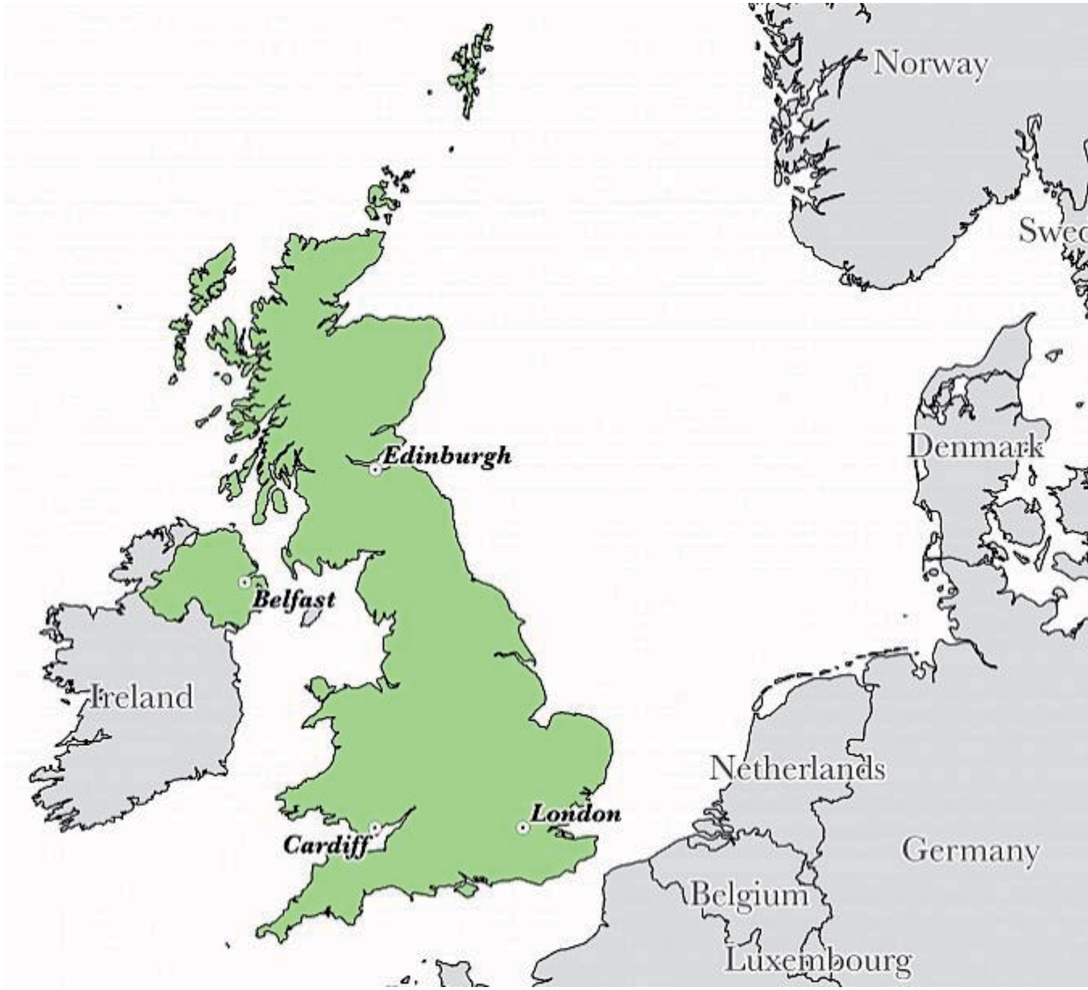
- Whole life maintenance and repair should be thoroughly considered during the design stages
- Facilitate access to and inspection of critical elements
- Modern design codes could be strengthen to ensure more focus is placed on designing in durability and maintenance
- D&B contractor is typically focussed on reducing capital cost and is usually not incentivised to make provisions for maintenance and whole life considerations

SITUATION IN THE UNITED KINGDOM

- 3,441 bridges (4.6%) are not fit to carry the heaviest vehicles, including lorries of up to 44 tonnes
  - Weight restrictions
  - Under programmes of increased monitoring
  - Managed decline
- Total cost of clearing the backlog of work on all bridges – including those that are substandard – is estimated at £5 billion
- Annual spend on maintaining bridges is £367 million, a decrease from previous years



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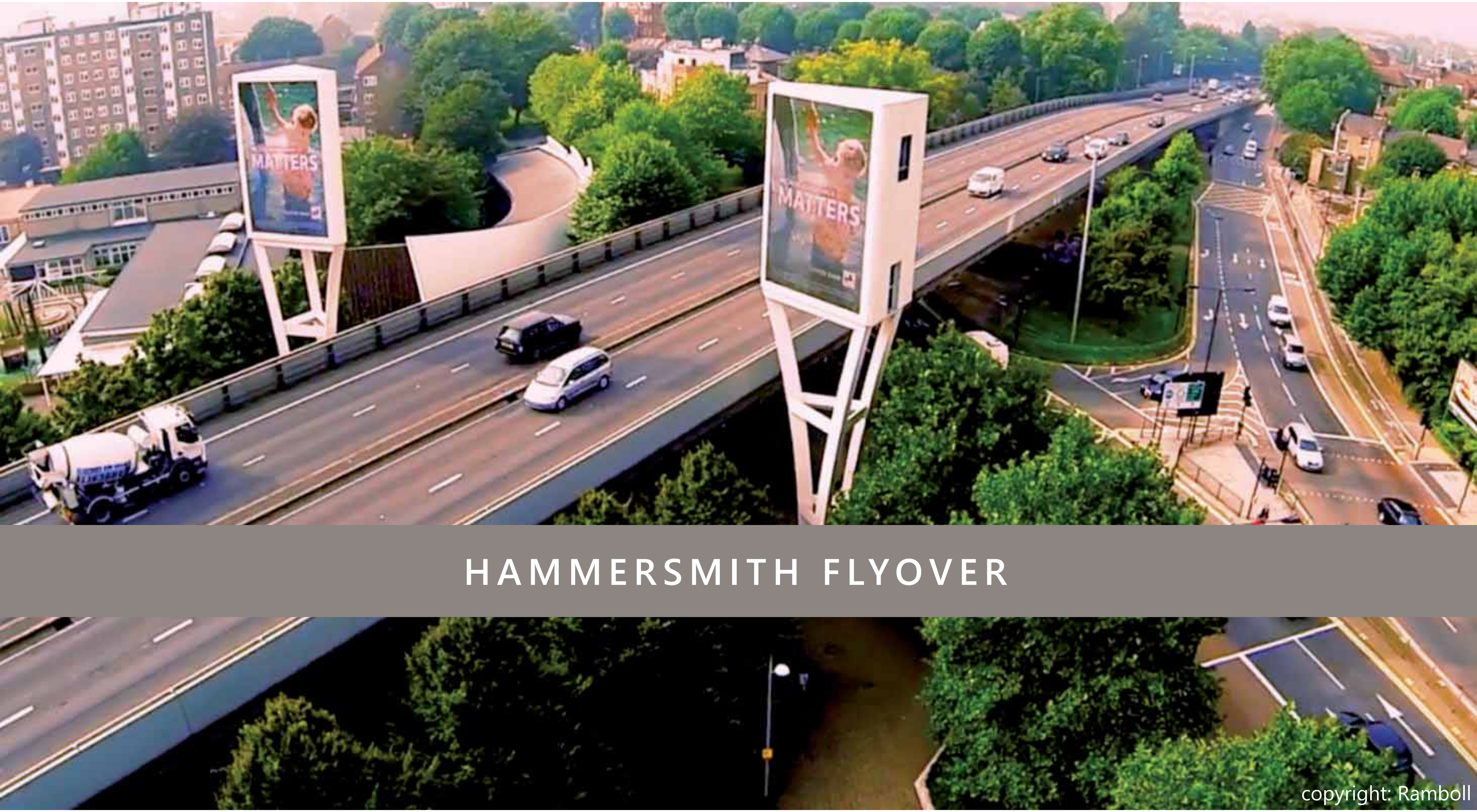

HAMMERSMITH FLYOVER

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HAMMERSMITH FLYOVER BACKGROUND

- 622m long flyover was constructed in the early 1960s and carries 80,000 vehicles a day
- First major segmental precast post-tensioned highway structure in the UK
- Key part of London's major highway link to Heathrow Airport and the west of England
- Grout was intended to protect the prestress tendons from corrosion
- Not designed to be subjected to de-icing salt, but provided with electric deck heating
- Heating was discontinued due to high electricity bill and later became defective

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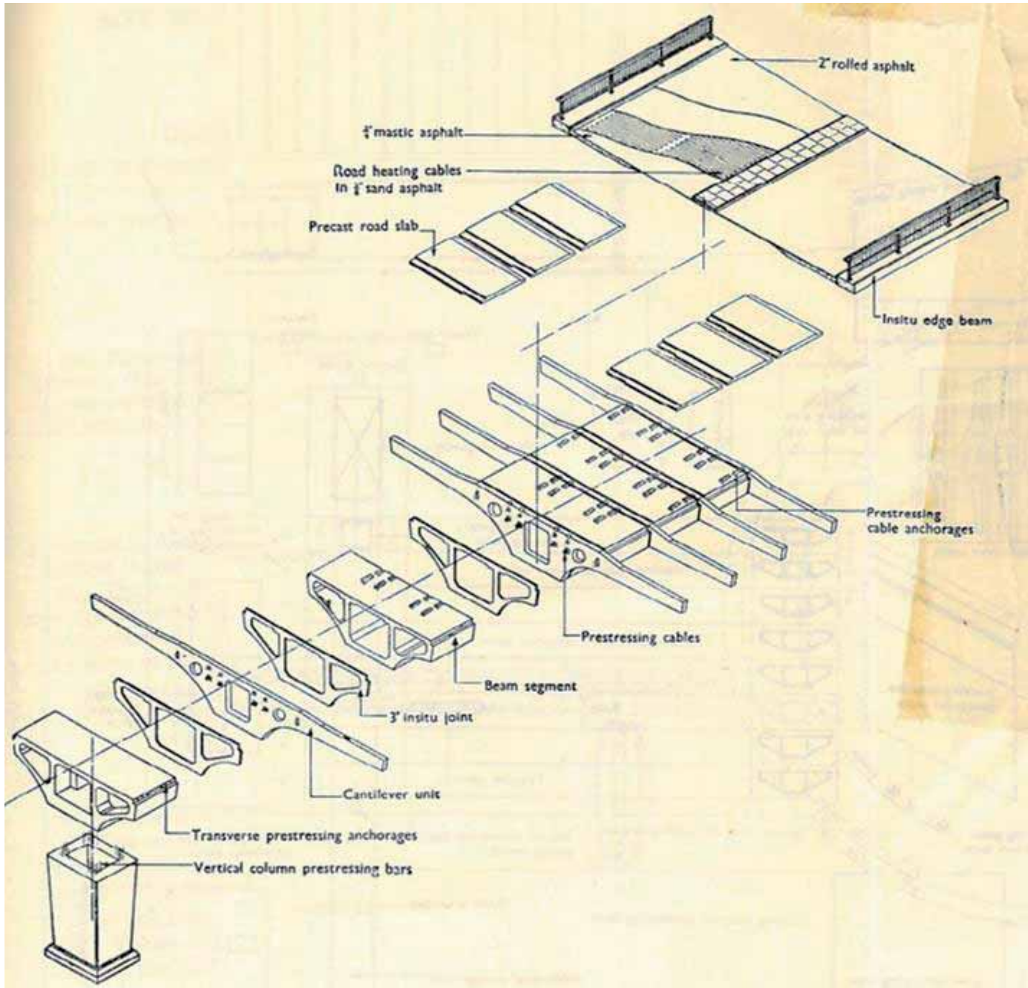

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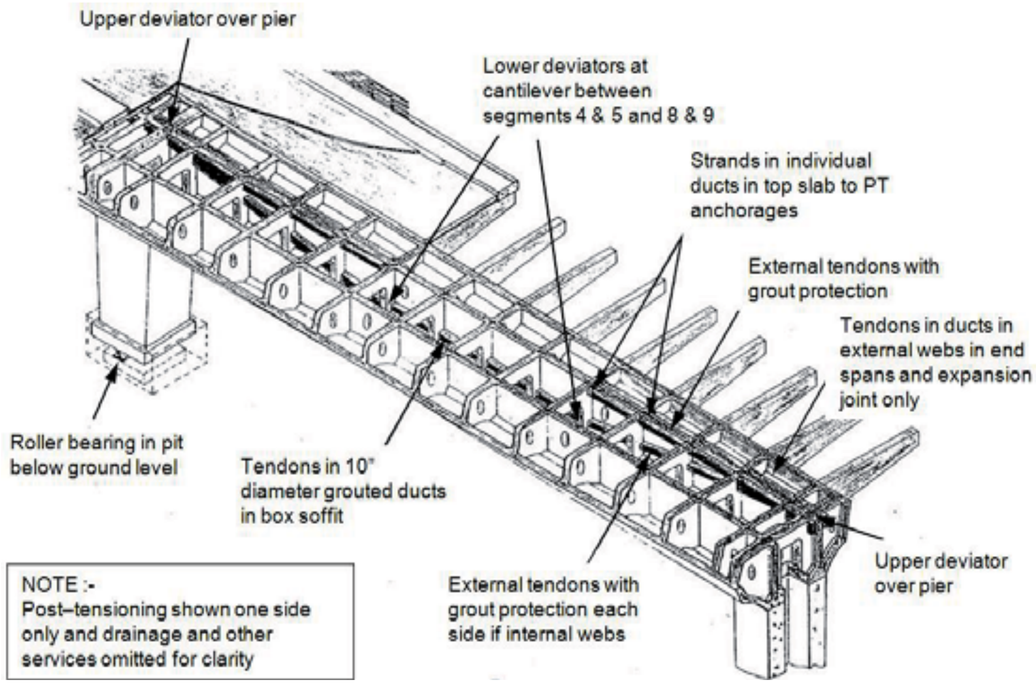
HAMMERSMITH FLYOVER CORROSION

- Post-tensioning tendons were corroding due to the ingress of water and chlorides from de-icing salts (1999)
- Work began to slow down the corrosion process
- Further inspections revealed significant deterioration in the tendons (2009)
- Largest structural monitoring programme in Europe
- 400 acoustic sensors on the eastern section to detect wire breakages in the prestress tendons



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HAMMERSMITH FLYOVER CORROSION

- Initial monitoring estimated 10 years until significant works would be required
- Significant increase in the rate wires breakages observed in 2011, one wire break a day!
- Emergency temporary propping was undertaken
- Extensive voids in the grout and active corrosion of the tendons beyond previous estimates: closing the Hammersmith Flyover
- Detailed assessment approved maximum vehicular load of 7.5 tonnes (previously 44 tonnes) and a vehicle width limit of 2m

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HAMMERSMITH FLYOVER STRENGTHENING

- Two distinct and separate phases of work to strengthen the flyover:
  - Pre-2012 Olympic Games strengthening, to enable full traffic load
  - Restore the capacity of Hammersmith Flyover for at least the next 60 years without requiring major maintenance
- The works could continue throughout day and night within the lane restrictions without having any additional impact on traffic

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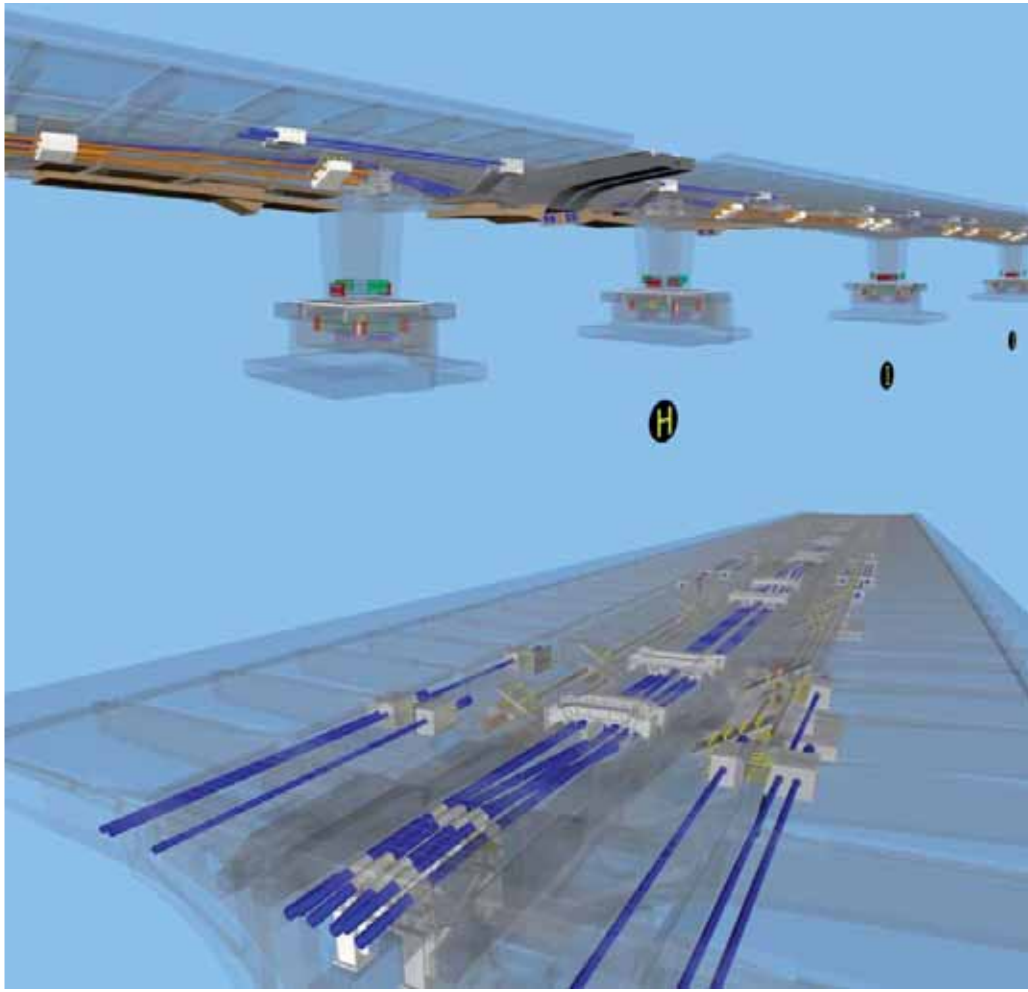
HAMMERSMITH FLYOVER
NEW PRESTRESSING SYSTEM

- Location of the new tendons; a critical issue as the optimum location was already utilised
- 3D modelling was used extensively both in the design and construction methodology for clash detection between the new elements and the existing structure
- 3D model helped inform, verify and challenge design assumptions and test construction scenarios
- Innovative solution: combination of long deviated tendons inside the box and short straight tendons largely outside were used



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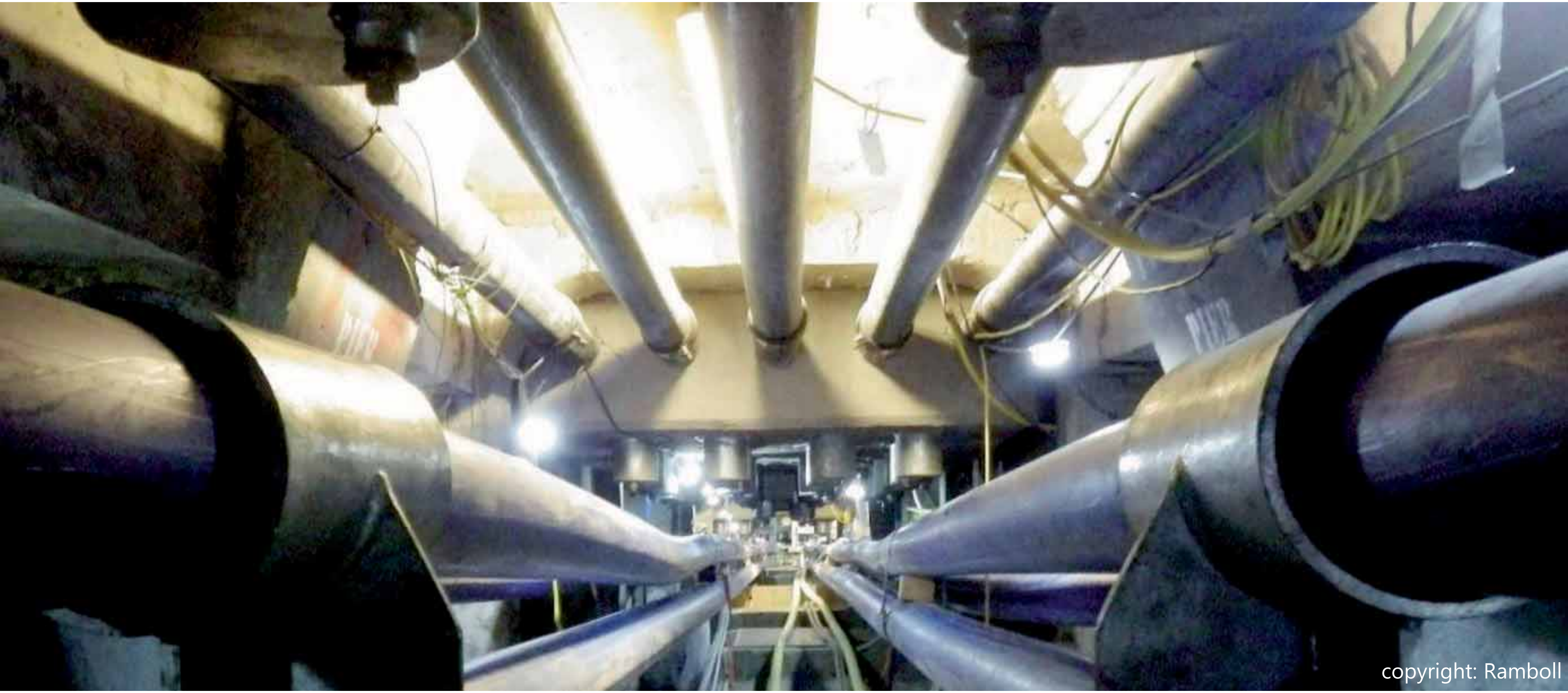
HAMMERSMITH FLYOVER
NEW PRESTRESSING SYSTEM: NEW INTERNAL TENDONS



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HAMMERSMITH FLYOVER
NEW PRESTRESSING SYSTEM: ANCHORAGE DESIGN

- Straight tendons are hot-dip galvanised and protected by polyethylene sheaths, and anchored with innovative ultra-high performance fibre reinforced concrete anchors (UHPFRC up to 170MPa)
- 192 innovative (bespoke) anchors, up to 1500mm x 900mm
- Minimise the additional stresses on the structure, but strengthening backing slabs was needed
- Long deviated tendons, up to 300m in length, are anchored in larger more conventional anchors

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HAMMERSMITH FLYOVER
NEW PRESTRESSING SYSTEM: UHPFRC

- Use of UHPFRC has raised the bar in the concrete repair industry
- UHPFRC has not been used in this application before in UK and design is not covered by the Eurocodes
- Successful testing by Freyssinet validated the performance under service loads, thus confirming the ability of the blisters to transfer the prestressing anchorage forces
- UHPFRC benefitted the new prestressing system with 50% reduction in size, only minimal conventional reinforcement required and lower weight of the concrete anchorage which enabled the minimum headroom clearance to be maintained for road users passing beneath the flyover
- Use of efficient off site precast manufacturing and testing techniques ensured consistency of product and full quality compliance

HAMMERSMITH FLYOVER
NEW SITUATION

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BRIDGES OVER THE FORTH

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BRIDGES OVER THE FORTH
BACKGROUND

- Three world class bridges spanning the Firth of Forth outside Edinburgh in Scotland.
- Each built in a different century and demonstrates a different bridge engineering solution, representative of the age:
  - Forth Bridge, cantilever, 1890
  - Forth Road Bridge, suspension, 1964
  - Queensferry Crossing, cable stayed, 2017
- Bridges present an evolution in the attitude towards long term maintenance at the design stage of bridges

BRIDGES OVER THE FORTH
THE FORTH BRIDGE

- Steel cantilever rail bridge constructed in 1890
- First major steel structure in the UK
- Originally designed as a suspension bridge, but withdrawn after the Tay Bridge disaster in 1879
- Very robust and overdesigned (“build and forget”)
- Principal maintenance issue is repainting of the large surface area of steelwork
  - Permanent maintenance team of painters
  - New 3-coat paint system

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BRIDGES OVER THE FORTH
FORTH ROAD BRIDGE

- Long-span suspension bridge and opened in 1964
- 4th longest main span in the world (1,006m)
- Twice the amount of traffic it was designed for crosses the bridge (25 million)
- Also attitude of “build and forget”
- After less than half of its original design life, the bridge began to show signs of significant deterioration

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BRIDGES OVER THE FORTH
FORTH ROAD BRIDGE: CORROSION OF MAIN CABLES (I)

- Two main cables are each made up of ~12,000 high tensile galvanised wires, 5 mm in diameter
- Pained in red lead paste and wrapped circumferentially with a galvanised wrapping wire
- Exterior of the wrapping wire was painted and finally a protective membrane was wrapped around the cables
- No way to inspect the main bridge wires without taking the wrapping wire off and opening up the cables to allow an inspection
- **In this respect it bears similarity to the Morandi Bridge in Genoa**

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BRIDGES OVER THE FORTH
FORTH ROAD BRIDGE: CORROSION OF MAIN CABLES (II)

- First suspension bridge in Europe to have its main cables opened up
- No exterior signs of deterioration
- Concern that corrosion might be present inside – as had recently been discovered in the cables of older American long span suspension bridges
- Unwrapping cable at selected locations and driving hardwood wedges into the bundle of wires
- Specially designed access gantries were used that could crawl up and down the cable independently, eliminating the need for traffic restrictions while work was in progress
- 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
- If deterioration could not be halted, the cable could lose 13% of its strength by 2014, and possible full closure of the bridge by 2020 (achieving less than half its design life)

BRIDGES OVER THE FORTH
FORTH ROAD BRIDGE: REMEDIAL ACTION

- Acoustic monitoring system (2006) to monitor future wire breaks
- Dehumidification system (2009): pumping dried air into the cables at low pressure, having first wrapped it in an airtight neoprene membrane with the aim of reducing the relative humidity to below 40% where corrosion cannot occur
- No further loss of strength has occurred since 2009
- Bridge is now expected to achieve its original 120 year design life
- Due to the uncertainty and immanent risk of closure, in 2007 it was decided to construct a new road bridge

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BRIDGES OVER THE FORTH
QUEENSFERRY CROSSING

- Cable stayed road bridge opened in 2017
- 2.7km structure is the longest three-tower, cable-stayed bridge in the world
- By far the largest to feature cables which cross mid-span
- Innovative design provides extra strength and stiffness, allowing the towers and the deck to be more slender and elegant

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BRIDGES OVER THE FORTH
QUEENSFERRY CROSSING: LONG TERM MAINTENANCE

- Evolution in the attitude towards long term maintenance in bridge design
- Integrate whole life maintenance
  - Monitor condition and behaviour
  - facilitate the repair and replacement of components, if required
- Builds on experience from around the world and marks departure from “build and forget”
- Provisions to facilitate inspection and maintenance have been built into the design
  - strands can be individually replaced without the need to restrict traffic

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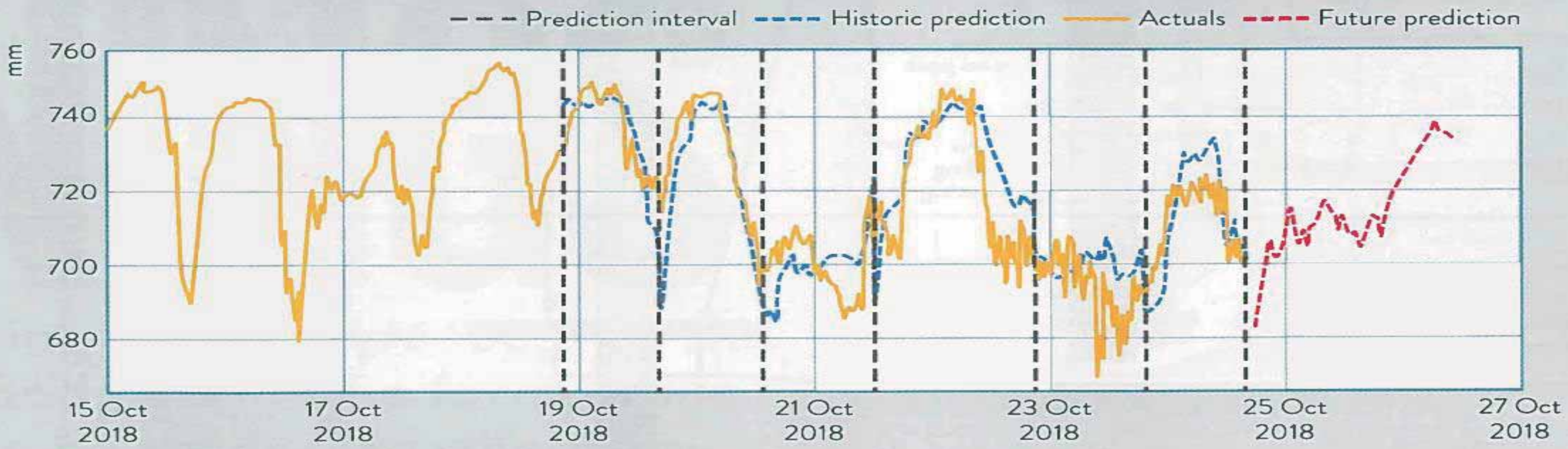
BRIDGES OVER THE FORTH
QUEENSFERRY CROSSING: STRUCTURAL HEALTH MONITORING

- 1,000 sensors have been installed to monitor wind, temperature, corrosion, motion and strains on the bridge and its environment in real time
- All data will be stored to allow data analytics identifying trends in behaviour
- Recently machine learning has been added which will enable it to use historical data to identify trends or behaviours not yet recognised by the maintenance team
- Make predictions about what safety measures or repairs should be carried out in advance of forecasted severe weather events
- Bridge operator to respond quickly to extreme events, to target inspections and to carry out pre-emptive interventions to avoid potential failures
- Long term data can be analysed and ensure better investment decisions are made

BRIDGES OVER THE FORTH
QUEENSFERRY CROSSING: MACHINE-LEARNING

MACHINE LEARNING – DISPLACEMENT PREDICTION OF BEARING ON NEW END-POST DETAIL



The graph shows how, based on historic bearing displacement readings and temperature and wind speed records, Mercury can predict bearing displacement (red). At each vertical dashed grey line, a new prediction is made based on the weather forecast at that point in time. Comparing the actual readings to date (orange) with the predictions made (blue) shows close correlation and, hence, confidence in predictions going forward. Prediction made on 23 October.

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BRIDGES OVER THE FORTH
QUEENSFERRY CROSSING: TECHNOLOGY AIDING INSPECTION WORK

- 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
- Advanced monitoring system and inspection technology has been deployed on the Forth Road Bridge as well, improving the structural health of both bridges
- Both bridges are brought into an integrated "managed crossing scheme" safeguarding the future of this vital road link for the UK
- Use of such technology in bridge inspections is still new in the UK

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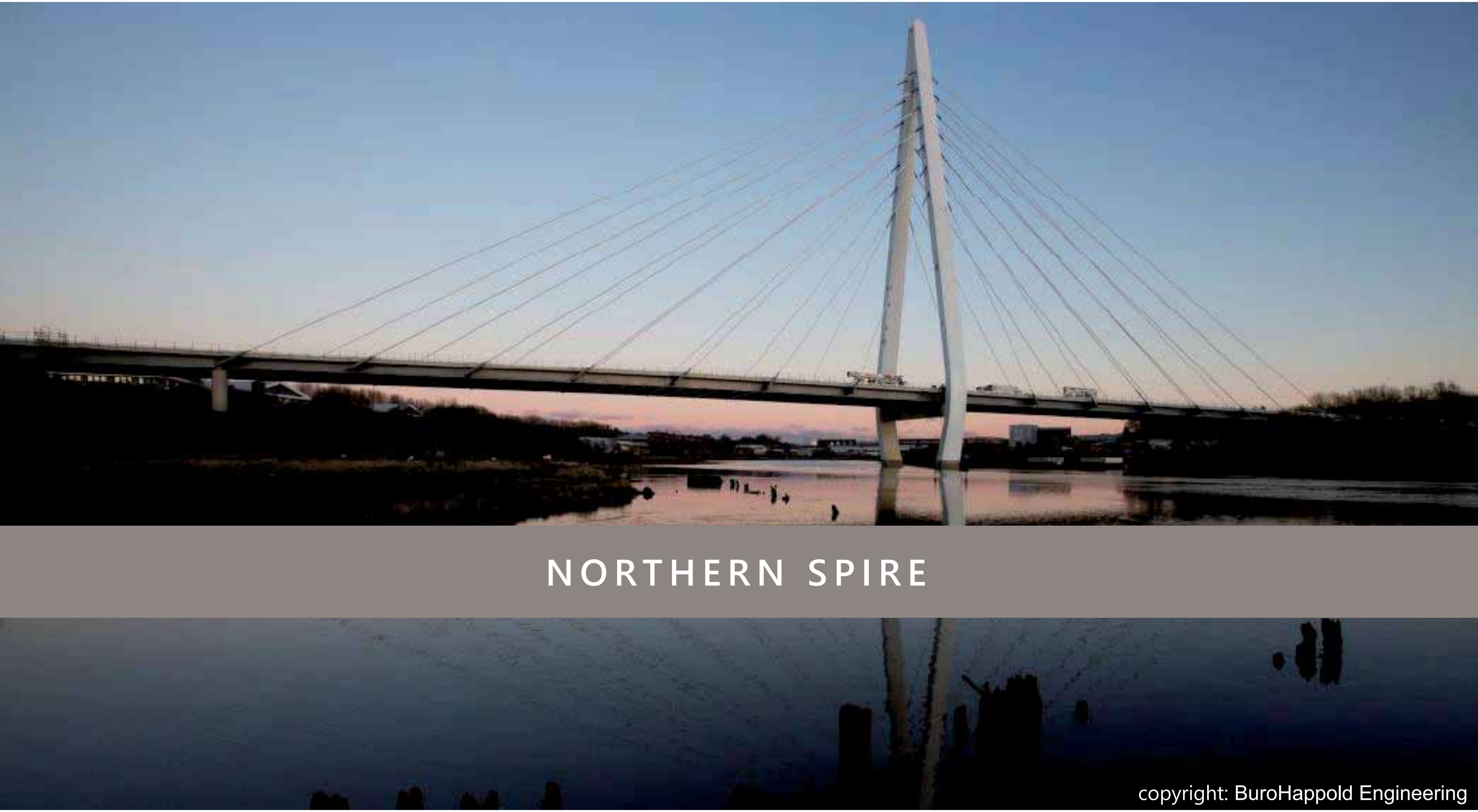
NORTHERN SPIRE



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NORTHERN SPIRE BACKGROUND

- Imposing two span cable-stayed bridge with an A-frame pylon
- First new road bridge in Sunderland for more than 45 years
- Forming a major part of the regeneration of the North East of England
- Whole life approach to bridge design is key in each design stage
- Minimise maintenance requirements and to facilitate ease of maintenance

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NORTHERN SPIRE
MAKING THE VISION VIABLE WITHOUT DISREGARDING MAINTENANCE

- Catered for future access requirements of a principal inspection
- Adjustable and fixed end anchors are located at deck level and within the pylon
- Access has been fully integrated into the principle structure
- 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 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

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NORTHERN SPIRE
INCLUDED LESSONS LEARNT

- Cable strands individually replaceable
- Dehumidifying system installed in internal steel pylon
- Outer layer of reinforcement in stainless steel to minimise the need for future repair works
- Electrical service ducts are accessible from abutment galleries. Junction boxes accessible from opening in the bridge deck
- Additional service ducts provided for possible future services
- Minimisation of number of bearings, including elimination of bearings at pylon location, and added robustness and future-proofing by extra load and movement capacity of bearings
- No bearings located over water (nor therefore subject to direct salt water spray)
- Jacking points provided at all bearing locations
- Highly durable elastomeric expansion joints which do not require replacement

M8 HARTHILL BRIDGE, LANARKSHIRE, UNITED KINGDOM
BREATH-TAKING BRIDGE DESIGN AND STRUCTURAL SAFETY

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LILLE LANGEBRO, COPENHAGEN, DENMARK
BREATH-TAKING BRIDGE DESIGN AND STRUCTURAL SAFETY

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NEW DANUBE BRIDGE, BUDAPEST, HUNGARY
BREATH-TAKING BRIDGE DESIGN AND STRUCTURAL SAFETY

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