Cite this article
Cousins DP, McAra D and Hill C (2025)
Monitoring of the Queensferry Crossing, Scotland.
Proceedings of the Institution of Civil Engineers – Bridge Engineering **178(1)**: 52–66,
https://doi.org/10.1680/jbren.22.00018

Research Article
Paper 2200018
Received 29/04/2022;
Accepted 19/10/2022;

Bridge Engineering

Monitoring of the Queensferry Crossing, Scotland

1 **David Peter Cousins** CEng, MICE
James Fisher Strainstall, Bristol, UK (corresponding author:
d.cousins@james-fisher.co.uk)

2 **David McAra** CEng, MICE
BEAR Scotland, Edinburgh, UK

3 **Chris Hill** CEng, MICE
Arup, Edinburgh, UK


1


2


3

The Queensferry Crossing opened in 2017 to enhance the resilience for road vehicles crossing the Firth of Forth outside Edinburgh, Scotland. The M90 carriageway consists of two lanes of traffic in each direction and hard shoulders. The three-tower, cable-stayed structure extends for 2.7 km, including approach viaducts. Structural health monitoring was specified by the employer in the construction works including 2184 physical sensors, which is believed to be the world's largest bridge monitoring system. This paper describes the monitoring and its uses thus far. A load test was conducted in 2020, comparing the sensor data favourably to the design. The monitoring is now integral to the operation of the bridge for measurement of structural performance and the management of the route. Automated reports give analysis of fixed periods of time and further detail for specific triggered events in occurrences of high load, abnormal load movements and extreme weather. The user interface includes a threshold alert system informing of the need for specific inspection and maintenance regimes. Route management in winter and extreme weather response is enhanced with the inclusion of sensor data. Monitoring data are also being used for research at various universities, each of which is described in brief.

Keywords: bridges/full-scale tests/monitoring

1. Introduction

1.1 Overview

The Queensferry Crossing, near Edinburgh, Scotland, was opened to traffic in 2017, having established itself as the most significant Scottish construction scheme in a generation (Figures 1 and 2). Among other accolades, the structural health monitoring (SHM) system installed during construction is a landmark achievement. Comprising 2184 physical sensors, their control systems, data storage, processing, reporting and live displays; this is understood to be the largest bridge monitoring system in the world, at time of writing.

This paper describes the monitoring installed, along with the key functionality and uses of the data. It provides additional information on the previously published work by Riches *et al*. (2019) including the verification load test, and shows the subsequent developments as the bridge has entered routine operation and maintenance. Lessons learned through the implementation and transition to operation are shared.

1.2 Literature review

Structural health monitoring has been readily available for assistance in the management of bridges since the 1990s and is quickly becoming more common. Studies have found that visual inspections for bridges suffer from limitations of access, safety and variability in the data collection (Lea and Middleton, 2002; Moore *et al*., 2001) and some asset owners aspire to applying digital measurement technologies further (Bennetts *et al*., 2020; McRobbie *et al*., 2015). Major bridges are now frequently constructed with SHM from their outset and are actively used for operation and maintenance.

A comprehensive review by Li and Ou (2016: p. 44) presents the technologies and their applications specific to cable-supported bridges, including a definition, endorsed by the current authors, as follows.

> Structural health monitoring technologies can be regarded as a tool to ensure the safety, serviceability, durability, and sustainability of structures employing long-term real-time monitoring. An instrumented structure is an in situ experimental system that records real

Figure 1. Queensferry Crossing and the Forth Road Bridge (background)

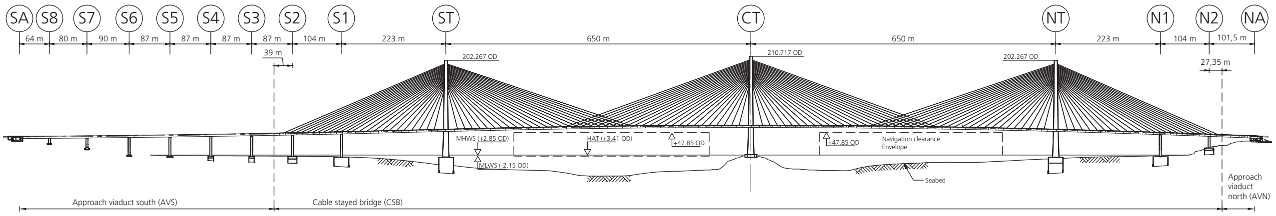


Figure 2. Elevation view

> loads, environmental conditions, real behaviours, and real evolution processes of performance of a structure during its service time… which will assist proper maintenance decisions and provide feedback for life-cycle performance-based design and construction.

Webb *et al*. (2015) defined five use cases for SHM, which are (*a*) anomaly detection, (*b*) sensor deployment studies, (*c*) model validation, (*d*) threshold checks and (*e*) damage detection. The Queensferry Crossing system does not set out to trial any new sensory technology but implements the other four objectives extensively.

Data collection alone is of little benefit other than research, but the extraction of useful information and the presentation in accessible forms can provide the bridge operator with guidance for optimal decision making. Davila Delgado *et al*. (2017) described the novel display of data by colours and overlaid on imagery of the small bridge concerned; an aspect which is furthered for the Queensferry Crossing, as described below.

In Japan the need for SHM on bridges is enhanced by the risk of earthquakes and typhoons, as shown by Fujino and Siringoringo (2011). The Queensferry Crossing also has its own environmental hazards, including ice accumulation, for which monitoring has been used to determine the risk. The same paper points out the need for advanced technologies to assist as labour resources diminish, and that this is not applicable for large bridges alone; the same can be applied for deterioration in ageing bridges of all scales.

Advances in the monitoring technology used have been demonstrated in Stonecutters Bridge, Hong Kong (Ni and Wong, 2012) with 1505 sensors and 1915 Çanakkale Bridge, Turkey (Tekin, 2018) with 1274 sensors. Likewise, in these cases, the aim was to take raw data and present actionable information in ways most appropriate to their respective management needs, extending to tying the data outputs into condition-based maintenance activities.

Cremona and Santos (2018) report that not only have the number of sensors greatly increased in recent years, but also the number of data streams on each sensor have increased and the sample rates have escalated. This trend means that these largest systems invoke the need for 'big data' management, and the methods and benefits from doing so are demonstrated.

1.3 Outline

Progressing from each of these previous examples and their lessons, the SHM system for the Queensferry Crossing serves as an example of how this is applied in practice. In Section 2 the bridge and its complexities are described in brief. Section 3 details the monitoring hardware and systems installed and Section 4 describes the full-scale load test applied, comparing monitored results to the design model. Section 5 describes the use of monitoring in bridge asset management. Finally, the aim of Section 6 is to share some of the most prominent lessons, and Section 7 looks ahead at areas of new research which are developing from the data collected.

2. Site study: Queensferry Crossing

The Forth Road Bridge opened in 1964 and carried all road traffic north from Edinburgh and back, over the 1006 m suspension span; by 2009, this traffic totalled 24 million vehicles per annum (Jacobs and Arup, 2009). In 2005, condition investigations of the main suspension cables raised concerns and led to prediction of a remaining life, and estimation of closure in 2018. Proposals for the Forth replacement crossing began, and received approval from Scottish ministers in 2007.

Plans were developed and contract awarded for the design and build to the Forth Crossing Bridge Constructors (FCBC) in April 2011, a consortium of contractors (American Bridge, Dragados, Hochtief and Morrison Construction) and their design entity, Forth Crossing Design JV, a consortium of consultancy firms (Ramboll, Grontmij, Gifford and Leonhardt Andra and Partner). The aspirations were finally realised in September 2017, when the Queensferry Crossing formally opened.

Subsequent further investigations of the Forth Road Bridge and management measures implemented by the then managing agent, Forth Estuary Transport Authority, and later Amey, led to extensions of the life prediction and use of the bridge as a dedicated public transport corridor.

2.1 Construction

Construction works started in April 2011. More complete information about the design and construction is detailed by Watt (2017), but a summary here serves to demonstrate the complexities and most notable features.

The three-tower cable-stayed structure makes use of a small rock outcrop in the river channel, but inherently suffers from a lack of restraint to the centre tower because it has no cables extending back to anchor into the ground. After diverse options had been explored, an innovative design involved the use of crossing cables at mid-spans to extend the stiffness of the flanking (north and south) towers to the centre tower.

The bridge includes no movement joints, other than at either end of the carriageway. The superstructure is only rigidly connected to the central tower. Flanking towers include two bearings each, which restrain transverse deck movement against the pier, but permit free movement in both the longitudinal and vertical directions. Expansion joints at the carriageway ends permit movement up to 2.4 m.

The shipping channel beneath the south main span is a key route for petrochemical movements, naval and cruise ships, leading to a requirement that the channel had to remain open at all times during construction.

Additional innovations in the design and construction included use of newly developed specification for stone mastic asphalt surfacing, TS2010 (TS, 2015), laid simultaneously over the full width of the carriageway to prevent longitudinal joints, and translucent wind-shielding to 3.6 m above the road surface, enabling traffic crossings even in winds up to 40 m/s (90 mile/h) while still allowing road users the view out over the estuary.

The construction received numerous acclaims including:

- the tallest bridge towers in the UK, the centre tower reaching 210.717 m above Ordinance Datum (Romberg *et al.*, 2019)
- the world's longest three-tower cable-stayed bridge at 2.64 km (Curran *et al.*, 2019)
- the south tower foundation became the world's largest underwater concrete pour at 16 869 m^3, taking 15 days continuously (West *et al.*, 2019)
- the central tower with adjacent half-spans extended to create the world's longest freestanding balanced cantilever at 643.9 m (Guinness World Records, 2016) (see Figure 3).

2.2 Bridge management

Transport Scotland (TS) is the Scottish government's national transport agency responsible for overseeing its statutory obligation to maintain the trunk road network. In August 2020, BEAR Scotland were appointed by Transport Scotland for an 8 year period as the operating company of the highway network in south-east Scotland, taking responsibility for the management of all highways and structures within the region, including both the Forth Road Bridge and the Queensferry Crossing. At the time, some elements of the Queensferry Crossing construction were still being completed and have been handed over subsequently.

Figure 3. Cantilever method of superstructure assembly

The SHM is used to assist with routine management in various ways, as described below.

3. Monitoring installed

3.1 Specification

Specification documentation, titled the 'Employer's requirements', for the SHM was developed for the bridge design and build contract by the employer's delivery team (EDT), consisting of Transport Scotland, Jacobs and Arup between 2009 and 2011, having taken lessons from previous large bridge monitoring systems including Stonecutters and Tsing Ma Bridges in Hong Kong.

The aim of the specifications was to provide a system to support the effective operation and maintenance of the bridge, with the key priorities being to deliver sustainable maintenance budgets, free-flowing traffic and the safety of operatives and the travelling public. The system could provide real-time review of the structure, traffic and environmental loading, while gathering long-term data to identify changes in behaviour and inform maintenance decisions, such as bearing replacement, supported by data on the actual performance of components.

Installation of monitoring, and later the maintenance thereof, was appointed to specialist supplier Strainstall.

3.2 Hardware and network installed

The bridge was installed with 45 data acquisition units (DAUs) or 'nodes' networked by eight bi-directional fibre optic communication channels (Figure 4). Two main servers are positioned in the south abutment and the bridge management office, which can replicate each other, and either one can take over in the

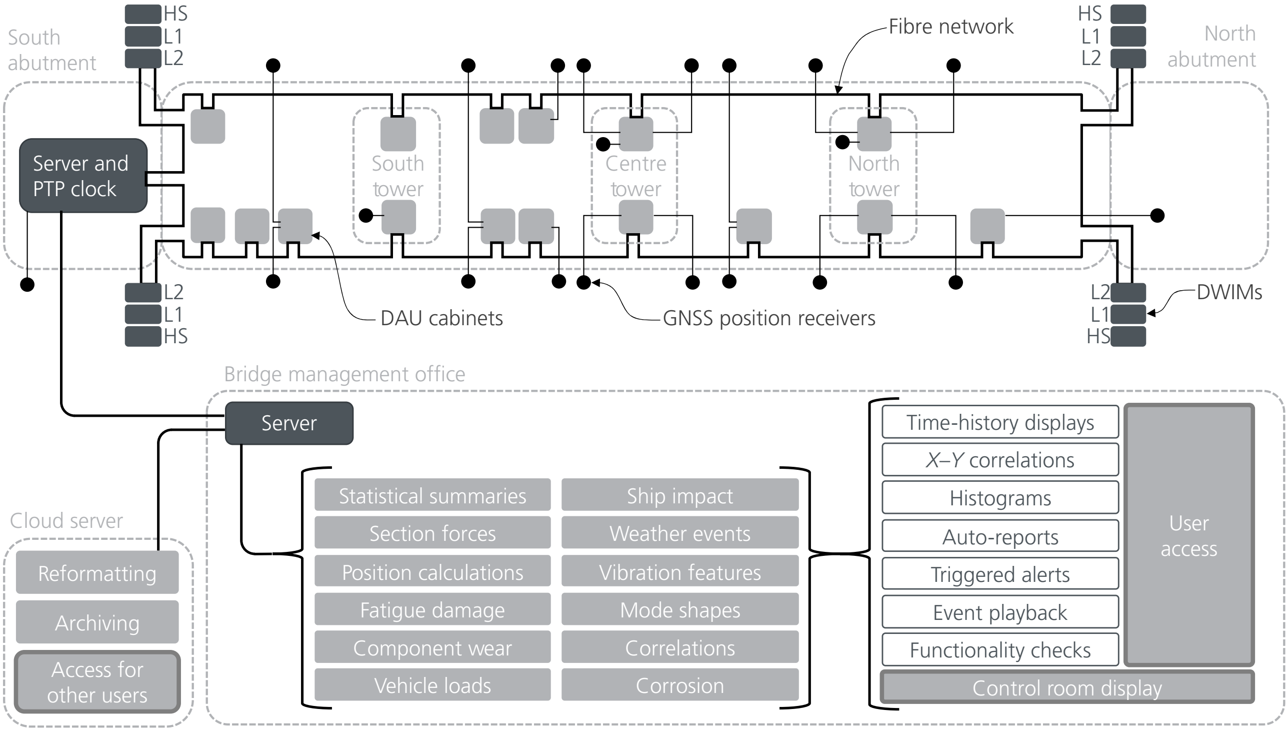


Figure 4. Schematic network of SHM

event of any failure. A satellite synchronised ‘grandmaster clock’ serves IEEE-1588 standard (IMS, 2008) precision time protocol (PTP) to all DAUs, by way of ‘boundary clocks’ for further precision. All data are synchronised to 100 ns or better.

The DAUs consist of various data loggers, amplifiers and control units selected to suit the sensors attached and their acquisition rates. Physical sensors, totalling 2184, are summarised in Table 1. Additional virtual channels are created by algorithms relating to one or more data streams incoming, for analysis and presentation. Fourteen terabytes (14TB) of hard drive space is provided in on-site servers, duplicated over two locations, which provides capacity for 185 days of data storage. Archiving and further back-up is provided off-site. Over 25TB of data storage is distributed among the DAUs, which allows temporary storage for 1 week, for resilience in case of any communication backlog.

Additional monitoring associated with closed-circuit television and management of smart motorway functions is not directly associated with the SHM and not included in this paper.

3.3 User interface

There are many different data formats collected on the bridge, each of which is structured according to the hardware and the respective manufacturers. Critical to the usefulness of the SHM is the single user interface for all data, which is the Strainstall software, smart asset management system (SAMS). By bringing all data into one comprehensive database, the user can have graphical displays and reports in a common form on one screen. Data from all sources can be compared seamlessly.

The highway network control room has one large display screen, capable of showing the current status at both the Queensferry Crossing and Forth Road Bridge. Users with access can view the same on their personal computer or smart device from any internet connected location.

3.4 Reports and outputs

Automated reports are generated in the software platform for periodic intervals, specific triggered load events, and these can be manually activated. Reports are in HTML format and include interactive graphical displays; extracts from examples are given in Figure 5. PDF report output options are also available, but the density of data makes these less favourable and they would be excessive to print on paper.

Multiple strain gauges are used in combination to calculate axial and bending force effects in the towers and superstructure. Sensors on the bearings are used to measure wear on the slide surface, predicting life expectancy. Measured accelerations are used to evaluate natural frequencies and oscillating mode shapes. (Such ‘virtual channels’ or variables calculated ‘on the fly’ are not included in Table 1, as these could potentially create infinite data streams on the same data.)

3.5 Alterations

The employer’s requirements were originally issued before the detailed design was conducted, giving items which later became unnecessary. Options in the employer’s requirements allowed the design and build consortium the possibility of a steel orthotropic deck, which was rejected in favour of a concrete post-tensioned deck on the steel U-section superstructure. This option removed the possibility of fatigue failures in welds beneath the road deck and hence SHM reports for detailed fatigue stress cycle counting were no longer necessary in these locations.

The employer’s requirements suggested a tree structure to the networked communications, involving 17 DAUs, each with daughter components. The selected data loggers for many items can be networked directly to the fibre loop and hence a flatter structure was used, with 45 nodes directly connected. This avoids the vulnerability inherent in larger parent components, losing communication to many sensors.

At the flanking towers, transverse movement of the deck is restrained against the tower by bearings, but these are free to move in the longitudinal and vertical directions. It was suggested that monitoring on the lateral bearings should be by direct measurement of both the vertical and longitudinal relative positions, with ranges up to 460 mm and 1040 mm, respectively. A typical solution is for spring-loaded gauges to be installed, pushing against a smooth sliding surface; however, this invokes maintenance problems, especially in such environmental exposure, and an increased risk in periods of data loss. Instead, the detailed design determined that a long linear potentiometer connected at each end by rose joints would measure the distance between both parts and a tilt sensor would measure the incline of the potentiometer. From this measurement, horizontal and vertical displacements can be calculated automatically as virtual data channels.

4. Load test

In August 2020, a physical load test was conducted using six heavy goods vehicles (HGVs) passing over the bridge in selected arrangements, with the exclusion of other vehicles on the same half of the carriageway.

4.1 Test purposes

The software system has a number of trigger levels associated with selected sensors and virtual sensors, which operate on combinations of physical sensor readings. If trigger levels are exceeded an alert is raised to the operating company, who

Table 1. Summary of sensors installed

Sensor type	Number of sensors	Typical usage	Normal sample rate: Hz	Maximum increased sample rate: Hz
GNSS positioning	21	Satellite positioning, including two static reference markers for correction. Each station creates multiple data streams for three-dimensional positioning and relative displacement	1	20
Tilt	48	Bi-axial incline of main towers at various heights, used for comparing tower curvature and hence estimating displacement at any height	1	20
Linear displacement	24	Longitudinal and vertical position of deck relative to piers. Slide surface wear on bearings	1	20
Ultrasonic distance	16	Deck end displacement at abutments, where other sensor types would be obstructive	1	20
'Static' vibrating wire strain gauge	292	Strains in concrete of piers and deck. Some were also used for temporary works during construction	1	20
'Dynamic' resistance strain gauge	504	Strain on surface of steel in superstructure and cable anchorages	1	1000
Corrosion detection	120	Corrosion in piers in the region of estuary water level. Data streams include: open circuit potential, corrosion current, resistivity, linear polarisation resistance, relative humidity and temperature	Responsive to readings	N/A
Dynamic weigh in motion (DWIM)	12	Piezoelectric sensors mounted in road surfacing just off the bridge, in each lane, approaching and leaving each carriageway. Data are processed automatically and evaluate variables for speed, mass and axle configuration of passing vehicles	Responsive to readings	N/A
Accelerations	102[a]	Accelerations and dynamic characteristics of cables, piers and superstructure	100	1000
3D ultrasonic anemometers	11	Weather conditions. Each sensor produces multiple data streams for wind speeds and directions. Reports evaluate 3 s gusts, 1 min average and 10 min average	1	50
Atmospheric (air) temperature	12	Weather conditions	0.02	N/A
Rainfall rate	2	Weather conditions	0.02	N/A
Relative humidity	252	Weather conditions	0.02	N/A
Barometer	2	Weather conditions	0.02	N/A
Temperature of asphalt road surfacing	40	Weather conditions, including the need of carriageway de-icing	0.02	N/A
Temperature of structural steel	158	Thermal influence on structural performance	0.02	N/A
Temperature of structural concrete	90	Thermal influence on structural performance	0.02	N/A
Temperature of stay cable	56	Thermal influence on structural performance	0.02	N/A
Temperatures for correction of strain measurement	375	Temperature compensation of dynamic and vibrating wire strain gauges	Suited to the respective strain gauges	N/A
Temperatures for DAU enclosures	47	Assists for remote checks of the monitoring system	0.02	N/A
Total	2184			

[a] A further 20no. tri-axial accelerometers make up a portable data acquisition system for which discrete mounting points are positioned throughout the structure and readings can be taken when required, including on all stay cables

would inspect the structure for potential damage locally. To provide confidence in the measurements and alerts raised by the monitoring system, the commissioning requirements of the SHM system stipulated by the EDT specifed a load test to be undertaken.

Of the many different sensor types installed on the bridge, the load test was intended to verify the behaviour of the global navigation satellite system (GNSS) receivers, tiltmeters and strain gauges. Measured values were compared by the EDT against theoretical values.

Forth replacement crossing – dynamic weigh-in-motion system report

This report is for the selected period of 9 October 2022 08:20:00 to 10 October 2022 08:25:58 and is generated from the raw data

Average of total flow in each direction (all vehicle types)

		Average total flow per			
		Hour	Day	Month	Year
Northbound	Hard shoulder	0	0	0	0
	Lane 1	359	8627	262412	3148947
	Lane 2	251	6032	183474	2201682
	Sub-total	611	14659	445886	5350630
Southbound	Lane 2	257	6164	187502	2250027
	Lane 1	347	8328	253317	3039720
	Hard shoulder	0	1	30	363
	Sub-total	257	6165	187533	2250390
Total		868	20825	633418	7601020

Based on 20911 vehicles counted between 9 October 2022 08:20:00 and 10 October 2022 08:25:58

Frequency distributions of axle weights in each traffic lane

Queensferry Crossing strain monitoring user defined report 16.1

This report is for the selected period of 05 September 2022 to 05 October 2022 and is generated from the 1 hour data.

Concrete towers and piers

Equivalent axial force

Series	Force (MN)		
	Max	Min	Mean
EAF-ST-OD126	24.05	–172.28	10.83
EAF-CT-OD7.5	128.87	23.14	82.96
EAF-CT-OD135	22.2	–180.69	5.6
EAF-N2-OD20	–9.51	–16.54	–12.74

North tower at + 126 OD: axial–moment interaction plot

Queensferry Crossing – corrosion – detailed report

This report is for the selected period of 28 August 2022 15:50:00 to 28 September2022 15:54:16 and is generated from the 1h data.

NT-OD11.10

Corrosion potential

Queensferry Crossing strain monitoring

User-defined report 16.4 (STN-3)

This report is for the selected period of 8 July 2022 15:50:00 to 15 July 2022 and is generated from the 10 min data.

Section STN-3

For graphing of data the section has been divided into three parts for steel deck element plus three sections for the concrete deck element. See drawing number MEP-008-D-PW-ITS-71908. Section A–A. West A to C1, centre C1 to F1 east F1 to H.

Axial stress in internal cross frame – west

Figure 5. Extracts from example automated data reports. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

4.2 Testing conducted

A convoy of six 44 t trucks was driven across the bridge at 20 km/h, arranged in two rows of three trucks with a 10 m separation between the rows (Figure 6). One truck in the convoy was fitted with a GNSS receiver to record the location of the convoy throughout the test.

The test was carried out under traffic management with a rolling road block on one carriageway of the bridge, repeating in each direction four times. The test was carried out overnight to minimise disruption to traffic and to reduce the effects of thermal variation during the test. With one carriageway open to public traffic, the presence of HGVs on the opposite side of the bridge could potentially affect the measured results, but the timing of the test and the difference in traffic speed between the carriageways meant the risk of obtaining no useful data was low.

The load test was conducted on Saturday 15 and Sunday 16 August 2020 between 10 p.m. and 4 a.m. The recorded wind speeds were low (below 10 m/s) and the recorded air temperature was 16.3°C falling to 16.0°C for the duration of the test.

The bridge is equipped with 19 GNSS receiver units (Figure 7), 16 are located on the wind shield and one at the top of each of the three towers (Figure 8). For increased accuracy, the system utilises a real-time kinematic correction, broadcast from two GNSS base stations located nearby but off

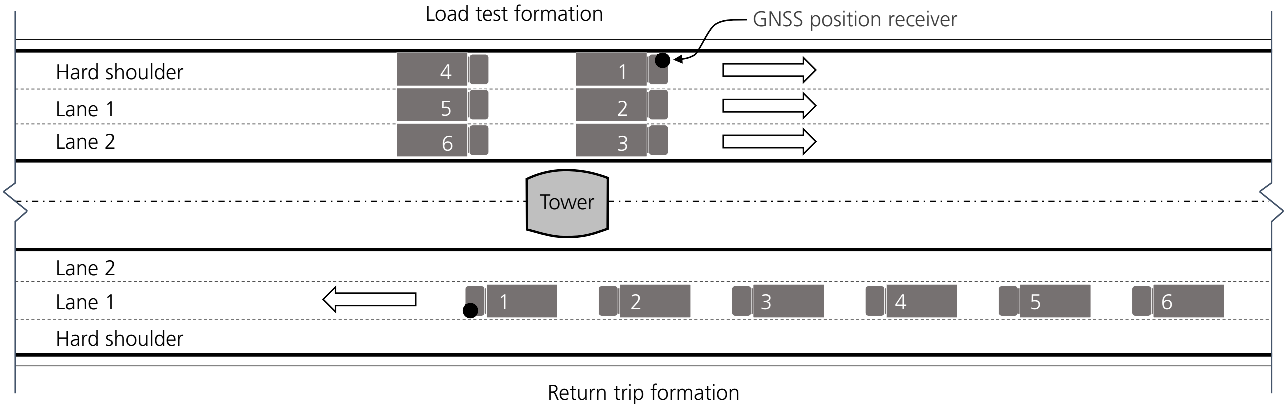
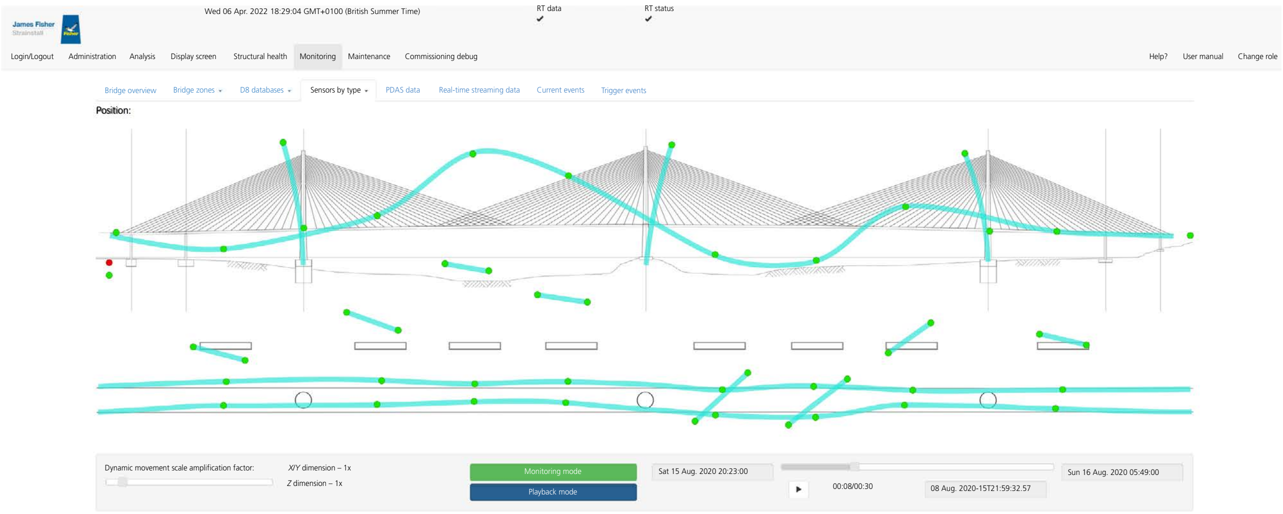


Figure 6. Truck convoy in load test



Wed 06 Apr. 2022 18:29:04 GMT+0100 (British Summer Time)

Position:

Dynamic movement scale amplification factor:

X/Y dimension – 1x

Z dimension – 1x

Sat 15 Aug. 2020 20:23:00

Sun 16 Aug. 2020 05:49:00

00:08/00:30

08 Aug. 2020-15T21:59:32.57

Figure 7. Locations of GNSS position receivers and exaggerated bridge deformation shape

the bridge, which give a positioning tolerance in real time of 10 mm horizontally and 15 mm vertically, improving to 3 mm and 5 mm, respectively, for static measurements.

Positioning of each GNSS receiver was sampled at 20 Hz throughout the test. For the deck sections, vertical displacement data were extracted and combined with the GNSS position data from the truck convoy, developing displays of load influence lines. The same was output from the employer's finite-element model for direct comparison. As the convoy is on one side of the bridge, the total measured vertical displacement is a combination of vertical and rotational displacement. The deck displacements are presented in Table 2, along with the correlation assessment criteria.

A good correlation was achieved between the predicted and actual values at most positions. One sensor with poor correlation, at location SS7, a result of a temporary loss of data, was included in the average processing. If this missing piece of data was removed, the difference was 19 mm.

Figure 8. GNSS positioning receiver on wind shield

For the tower top sensors, the passage of the convoy causes the towers to displace in the longitudinal direction of the bridge deck, which is aligned at approximately 20° from north. The GNSS receiver reports the displacement in the world geodetic system 1984 (WGS 84) coordinates. Horizontal displacements are transposed into vectors of the longitudinal (X) and transverse (Y) directions of the bridge.

The results are summarised in Table 3. Generally, excellent correlation was found between the measured and predicted data.

Similar correlation analysis was carried out for the tiltmeters.

Several strain gauges from the monitored cross-sections were found to be faulty during the test, particularly gauges embedded in concrete, which were damaged during construction. These severely affected the results to the point where no meaningful comparison could be made against theoretical section forces. In response, an algorithm to exclude erroneous results has been implemented within the software and the correlation analysis completed to verify the correct calculation of section forces from strains to conclude the commissioning process.

4.3 Test outcomes

The load test has demonstrated a good correlation between the monitored bridge behaviour and the analysis model, with the analysis model providing close and conservative prediction of the deck movement, within 10% or 10 mm of the actual deflection at all but one sensor location, due to a localised interruption in the generation of sensor data.

The load test gave confidence that sufficient sensors provide reliable results. Refinements will continue in the use of these data for further comparisons and repeat tests.

Table 2. Correlation of deck displacement

	Maximum value: mm				Minimum value: mm			
GNSS sensor	Model	GNSS	Difference	%	Model	GNSS	Difference	%
SS7 N/bound W	4	12	−8	−200	−62	−35	(−27)	44
SS7 S/bound E	4	7	−3	−75	−62	−58	−4	6
FS10 N/bound W	12	11	1	8	−120	−107	−13	11
FS10 S/bound E	12	10	2	17	−120	−117	−3	3
CLS N/bound W	60	57	3	5	−193	−179	−14	7
CLS S/bound E	60	54	6	10	−193	−192	−1	1
CS10 N/bound W	54	48	6	11	−128	−121	−7	5
CS10 S/bound E	54	51	3	6	−128	−114	−14	11

Correlation categorisation: Excellent correlation – agreement within 5%/5 mm; Good correlation – agreement within 10%/10 mm; Poor correlation – >20 mm difference

Table 3. Tower top displacement correlation in *X* longitudinal direction

	Maximum value: mm				Minimum value: mm			
GNSS Sensor	Model	GNSS	Difference	%	Model	GNSS	Difference	%
ST (top) N/bound	24	25	−1	4.2	−5	−9	4	−80
ST (top) S/bound	24	21	3	12.5	−5	−8	3	−60
CT (top) N/bound	54	48	6	11.1	−54	−47	−7	13.0
CT (top) S/bound	54	42	12	22.2	−54	−49	−5	9.3

Correlation categorisation: Excellent correlation – agreement within 5%/5 mm; Good correlation – agreement within 10%/10 mm; Poor correlation – >20 mm difference

5. Monitoring in use

The installed SHM system specified, designed and installed under the Queensferry Crossing construction contract is engaged by the operating company, BEAR Scotland, who utilise the vast output of data from the myriad of installed sensors to monitor the behaviour of the bridge during normal operation and exceptional loading events. The data will also help determine future maintenance requirements.

As a bridge operator, BEAR Scotland observes the real-time data, which helps inform managers to implement necessary restrictions or closures. More recently, temperatures recorded on the stay cables and towers help to inform regarding the forecasting of ice accretion. Dynamic weigh-in-motion (DWIM) data track the use of the bridge by heavy vehicles. Anemometer wind speed readings identify the need to impose speed restrictions for crossing vehicles.

5.1 Use of the SHM system

The installed SHM system allows the operating company, in conjunction with the bridge owners, to make better decisions and lead to a safer, more reliable and resilient structure. Data and the automated reports received from the SHM are intended to play a significant role in determining the need for planned maintenance on components such as bearings. Thus, the need for reactive maintenance should be greatly reduced and disruption to the travelling public kept to a minimum.

The Queensferry Crossing SHM has the functionality of automated alerts, with alarms raised if certain structural response, applied effects, environmental thresholds or trigger levels are reached. Trigger levels are set at 80% of serviceability design limits for environmental sensors, including anemometers and temperature gauges. Structure response sensors, including GNSS positioning, tilt meters and strain gauges have trigger levels set at 80% of serviceability design predicted effects. The trigger levels are set conservatively, and no damage is expected.

Following the triggering of an alarm or any extreme event, the operating company undertakes a special inspection to determine whether the safety of the structure has been compromised and identify any areas of damage that may have occurred. If damage is noted local to the triggered sensor locations, the inspection and maintenance manual identifies further regions to which the inspection should be extended.

Following an extreme event, the SHM produces reports which include correlation of the monitored load or load effect with the predicted design limits (at serviceability and ultimate limit states) and detail the bridge responses (forces, moments, deflections) compared to design values. A summary of utilisation factors of critical deck and tower sections is provided for further review.

The use of SHM data and monitoring reports helps to inform the operating company of future maintenance requirements on the structure. Automated ‘service life monitoring reports’ evaluate the remaining functional life of replaceable and vulnerable components, including fatigue-sensitive elements, bearings and expansion joints. Each takes the readings from multiple physical sensors, creates ‘on-the-fly’ virtual variables by algorithms and presents summary details in the output reports.

BEAR Scotland provides Transport Scotland with regular updates on the performance of the structure, with routine reports issued on a quarterly basis and an annual interpretive report to

- summarise the data gathered for each sensor type
- present interpretation of the data, including any trends or results which are not as expected
- give any recommendations for extended analysis required to support any maintenance.

5.2 Abnormal load movements

The DWIM systems are positioned just beyond each end of the bridge, with piezoelectric sensors laid beneath the surface of the carriageway of both traffic lanes and the hard shoulder. Real-time streaming is available to view within SAMS, helping to monitor the passing of abnormal loads, which is compared against prior submission of movement notifications by haulage companies.

The DWIM system gives a full breakdown of the number of vehicles and associated categories passing during any requested period. The operating company is required to audit biannually 10% of vehicles with a gross weight greater than 80 t, for which the DWIM system provides directly comparable data.

Data are analysed to determine the requirement for structural inspections following the transit of an abnormal load. If a trigger level comparable to the weight of a design vehicle (BSI, 2003) is exceeded and strain measurements exceed 80% of the design value, additional visual inspections shall be undertaken.

5.3 Extreme weather

The adjacent Forth Road Bridge has been subjected to many closures since its opening in 1964 in conditions of high wind, predominately from a westerly direction down the Firth of Forth. When designing the Queensferry Crossing, the bridge owner and the designers aimed to ensure that the bridge would remain open, even during the highest of wind speeds by incorporating a wind shield barrier 3.6 m high along each parapet.

The bridge has a total of 11 three-dimensional ultrasonic anemometers located at mid-span points on the deck and at the top of each tower. If, during a high-wind event, the recorded gust wind speed exceeds 39.1 m/s at the top of the central tower, or 35.0 m/s at deck level, then a series of predetermined inspections will be undertaken at structurally sensitive locations for the possibility of damage. It will also be possible for the multiple wind data sets to be applied into an analysis model, and the model to be interrogated for additional locations of high stress, then requiring further visual inspection.

5.4 Navigational clearance

Two of the main spans of the Queensferry Crossing extend over shipping channels, the Grangemouth channel to the south and the northern Rosyth channel. Forth Ports Scotland notifies BEAR Scotland of large air draft vessels scheduled to transit beneath the Forth bridges. During transit, the GNSS position markers located at quarter spans of the superstructure are monitored to ensure that, due to environmental and traffic loading conditions, the vertical displacement value does not exceed the permitted negative value, indicating a reduction in navigational envelope.

5.5 SHM maintenance

The monitoring system requires various proactive maintenance tasks, most of which are repeated at 6 month intervals, ranging from cleaning of rainflow ‘tipping buckets’ to calibration checks of analogue reading devices.

6. Lessons learnt

There are many lessons learnt and no doubt some errors that will be made again. The following is intended to provide a record of some that are perceived most useful for future applications.

6.1 Technologies move on

Between the writing of the SHM specification and the commissioning of the installed system, various technologies have not only become smaller and faster, but some have even changed form. The progress of cloud-based computing has led other monitoring systems in this time to move away from on-site servers. Specifications written in terms of the objectives rather than the means of achieving such, tend to allow more freedom for the contractor to implement these progressions.

6.2 The new and novel

In one regard, the ability to implement the employer’s requirements was not fully available on the commercial market at the point of developing specifications. It may have been considered aspirational and/or with an expectation that by the time the parts were to be installed, the products would have continued advancing. This relates to the sample frequency for vibrating wire gauges.

It is more normal to use vibrating wire gauges for ‘static’ measurements including thermal effects or ground movements. Traditionally, vibrating wire measurements involve a sequence of gauge excitation, followed by reading the frequency response returned. This limits sampling to typically 1 Hz. The frequency reading is used to calculate change in strain and is then corrected for temperature.

In the Queensferry Crossing, vibrating wire gauges are used to measure strain in the concrete deck due to the static dead load and post-tensioning effects, slowly varying effects such as the temperature and the dynamic effects of passing wheel loads. Because of the latter, they are required to sample at 20 Hz (20 samples/s).

The very newest commercially available products were selected for the data acquisition components to achieve these objectives. Within 3 years of installation, from 47 sensor reading modules, 25 were deemed faulty or inadequate and were replaced. In that time, the manufacturer had withdrawn the product and replaced it with an improved alternative; better reliability is now achieved.

6.3 Installation during construction

The SHM was installed during construction. Gauges embedded in concrete for corrosion and strain monitoring must be installed before concrete pouring. Monitoring can be used for geometry control during assembly, although this was not applied for the Queensferry Crossing. Other gauges, data acquisition systems and communications routes, however, could be installed after the structure is complete.

Numerous problems were encountered in conflicts between construction activities and SHM installation. Sensors were damaged, water ingress was a persistent issue, working areas conflicted and access provisions were not fully ready, including the tower lifts and the underslung gantry system. SHM installation could have largely been retrofitted shortly after construction, saving installation time, cost and replacement parts.

6.4 System modifications for usage

The SHM was specified by parties involved with the bridge design. The ethos used agrees with their concepts for how the bridge might be expected to behave and the confirmation thereof. When the SHM came to be applied for the day-to-day operations of highway management, it proved desirable to adjust some features. One such area was the active displays.

The SHM system was largely determined to create discrete reports of data for specified periods of time (mostly quarterly) or in response to a triggered event (extreme weather or high loads). Although a report provides comprehensive information, it does not give an easy oversight of the current condition at any given time. BEAR Scotland and Strainstall worked together to develop a dashboard which became known as the 'sea of green', as shown in Figure 9.

Sixty-three dots are positioned over an elevation view of the bridge representing sensors close to their physical position, confirming by the colour green that they are online. A group of sensors not responding is highlighted by the respective marker on the elevation view pulsing with red radio signals.

Beneath the elevation view, 63 rectangles depict by colour the current readings on a related group of physical and/or virtual sensors associated with a particular condition of the bridge. Green and yellow indicate normal readings. Amber indicates the lower alert threshold is being exceeded, and for some criteria activates increased sample rates or requires a physical inspection regime. Red indicates an upper alert threshold has been exceeded. Grey indicates no communication for a period of time. Since each rectangle responds to multiple sensors and criteria, there is a hierarchy of colours ensuring that red and amber are prioritised, since these may require immediate actions. Wind roses and temperature gauge visualisations convey environmental conditions.

Specifications for the operating company require periodic and responsive reporting to Transport Scotland, which differed slightly in a few places from the SHM details. Adjustments were made in the software to the reporting periods and functions were added to assist in displaying the performance of the

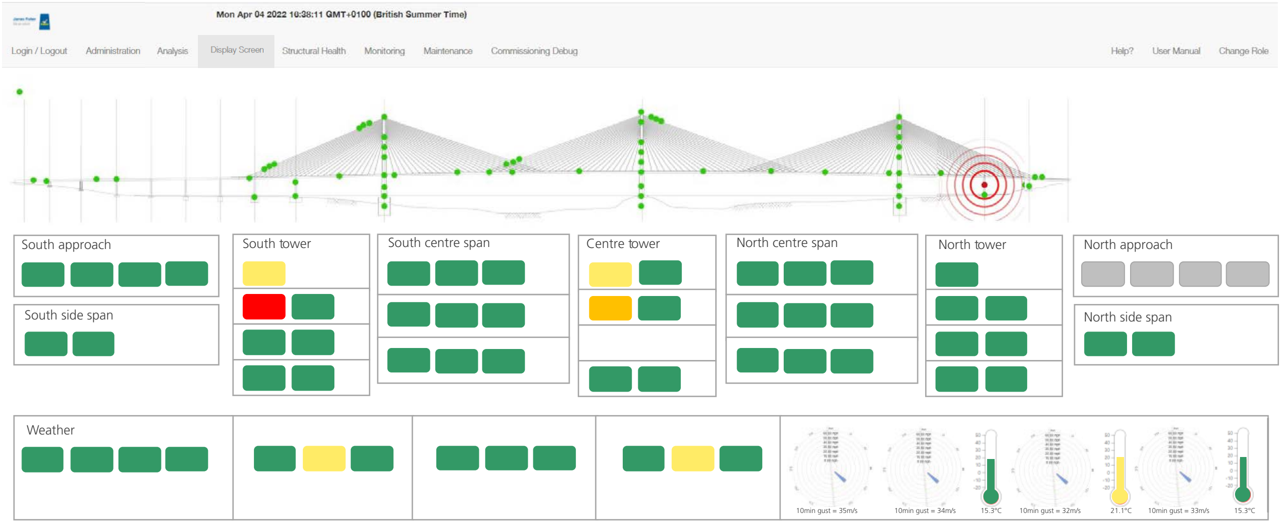

Mon Apr 04 2022 10:38:11 GMT+0100 (British Summer Time)

Figure 9. Dashboard display for bridge management control room (the sea of green). A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

SHM system itself. A periodic report was added giving graphical displays for the proportion of 'up time' for each DAU and sensor to help identify faults.

6.5 Data storage and archiving

The employer's requirements stated a need for site data capacity equal to accommodate what would be created in 185 days (6 months). Assumptions in the frequency of triggered events were agreed and hence the data storage was sized accordingly at 14TB. However, it was not intended that data older than 6 months would be deleted. Functions were later implemented to address this.

All data are exported from the on-site servers to a cloud platform for secure archiving. A new data structure was developed to divide data into 10 min files unique to each sensor, thereby easing the reuse in other data platforms and speeding the ability to find specific data sets later.

A series of summary files in the on-site servers holds data beyond 185 days. The mean, minimum, maximum and standard deviation of data are kept for time periods ranging from 3 s to 1 h on each data stream. This enables graphical displays for the user, depicting a longer historical record albeit without the very finest resolution at the longest time ago. The relative size of the summary files is very much smaller than the full data sets.

Ongoing learning of the bridge behaviour by review of the data will continue and rationalisation of the storage may be actioned later.

6.6 Sensor faults

A number of faults in the sensors and data acquisition system were discovered by review of the load test data. Components that had been commissioned and appeared to function correctly only revealed anomalies when compared to a known load and a predicted response. Without the load test, it might have taken some years to discover these items.

Algorithms that use multiple sensor values to calculate other variables are employed extensively. Such include the calculation of axial force and bending moments within the bridge superstructure at various cross-sections. These were found to be vulnerable to data gaps or abnormalities in any one or more channels. Later amendments applied rules to distinguish between reliable and unreliable data and selectively use appropriate force–effect calculation functions.

7. Research usage

Data have been made available to selected universities for research, including the following.

7.1 University of Edinburgh

Research at University of Edinburgh is investigating data-driven methods based on the physics of the structure (Xu *et al.*, 2019; Xua *et al.*, 2021).

Traditionally, the data from SHM systems were processed with simple statistical methods. To infer useful engineering parameters, an understanding is required of the complete sensor system of the bridge – including load input by way of the DWIM system and responses from the various strain gauges. Data from strain gauges embedded in the concrete of the piers can be processed to obtain information about the live load applied to the bridge, but they also contain the effects of temperature on both the sensor and the pier, as well as long-term creep and shrinkage of the concrete and other non-linear effects. Using the Queensferry Crossing data, recurrent neural networks are commissioned to predict the structural response based on both environmental and operational factors. Artificial anomalies have been added to the dataset to test the feasibility of the proposed neural networks on detecting outliers. This model can be used to compare the ground truth response and predictions.

7.2 University College London

Cable-stayed bridges are highly indeterminate structures. They exhibit subtle load-carrying mechanisms which can be exploited to improve robustness while minimising material consumption and geometric complexity. Monitoring of bridges in service provides an excellent opportunity to infer those mechanisms. The Queensferry Crossing is exceptional in providing a large bank of sensor data that enables quantification of both the loads (traffic and environmental) and the associated responses. Research at University College London is focused on interpreting these data to build a clear picture of the local and global load paths which define the structural mechanics of the bridge over the short term and the long term. The understanding is intended to be used to define a numerical modelling strategy that captures the essential bridge mechanics while minimising the associated computational power demands. This builds on ongoing laboratory and field studies alongside modelling work on various bridge forms, including cable-stayed (Franchini *et al.*, 2022), steel–concrete composite (Xu *et al.*, 2022) and fibre–polymer composite traffic bridges (Sebastian, 2021).

7.3 University College Dublin

Research at University College Dublin is exploring the applications of computational fluid dynamics (CFD) to the built environment (Bernardo *et al.*, 2021; McGuill and Keenahan, 2020). Traditionally, wind tunnel testing is used to inform the design process of accounting for wind effects on civil infrastructure, particularly for long-span bridges. However, there can be limitations to this approach in terms of scaling issues, descriptions to the flow from sensors and long lead times for repeat analysis. In this context, CFD modelling is coming to the fore, given its capacity to avoid scaling issues and model the dynamics of both the fluid and the structure (Zhang *et al.*, 2021a). Validation and verification of CFD models is essential (Zhang *et al.*, 2021b), and the availability of field data from long-span bridges is a particularly exciting opportunity. Ultimately, the field data are the 'true reality' of what the bridge experiences, and it will be invaluable to compare these with the approximations offered by both wind tunnel testing and CFD modelling outputs. Current work is exploring this for both the Queensferry Crossing and the Rose Fitzgerald Kennedy Bridge at New Ross in Ireland. While the potential impacts on the design process of bridges are significant, the impacts in the long-term operation of bridges will be equally important. There is limited guidance in the literature on the development of wind management plans for bridges. The impact of having fully validated CFD models for wind effects on bridges will offer opportunities to investigate high-wind scenarios, their risk to vehicles and the relative benefits of wind shielding in such scenarios (Zhang *et al.*, 2020).

8. Conclusion

The Queensferry Crossing has an extensive SHM system that was installed during construction. Used through interactive displays and reports, this enables the bridge to be managed through condition-based maintenance. A load test was conducted in 2020 verifying both the constructed structural behaviour and the performance of the monitoring system. Lessons shared should be applied to future similar schemes. Further uses of the SHM continue to be applied and research will expand the use in other areas.

Acknowledgement

The authors would like to thank Transport Scotland for their support to publish this work.

References

Bennetts J, Vardanega P, Taylor C and Denton S (2020) Survey of the use of data in UK bridge asset management. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* **173(4)**: 211–222, https://doi.org/10.1680/jbren.18.00050.

Bernardo P, Reamoinn RM, Young P *et al.* (2021) Investigation of the helicopter downwash effect on pedestrian comfort using CFD. *Infrastructure Asset Management* **8(3)**: 133–140, https://doi.org/10.1680/jinam.19.00060.

BSI (2003) BS EN 1991-2 Eurocode 1: Actions on structures – Traffic loads on bridges (and UK National Annex). British Standards Institution, London, UK.

Cremona C and Santos J (2018) Structural health monitoring as a bid-data problem. *Structural Engineering International, International Association for Bridge and Structural Engineering* **28(3)**: 243–254.

Curran P, Vasques A, Platt A and Baralos P (2019) Queensferry Crossing, UK: cable-stayed bridge deck and cables – design and construction. *Proceedings of the Institution of Civil Engineers* - *Bridge Engineering* **172(2)**: 135–144, https://doi.org/10.1680/jbren.18.00016.

Davila Delgado JM, Butler LJ, Gibbons N *et al.* (2017) Management of structural monitoring data of bridges using BIM. *Proceedings of the Institution of Civil Engineering – Bridge Engineering* **170(3)**: 204–218, https://doi.org/10.1680/jbren.16.00013.

Franchini A, Sebastian W and Dina D (2022) Surrogate-based fragility analysis and probabilistic optimisation of cable-stayed bridges subject to seismic loads. *Engineering Structures* **256(3)**, https://doi.org/10.1016/j.engstruct.2022.113949.

Fujino Y and Siringoringo DM (2011) Bridge monitoring in Japan: the needs and strategies. *Structure and Infrastructure Engineering* **7(7–8)**: 597–611.

Guinness World Records (2016) Longest free-standing balanced cantilever. Guinness World Records Ltd, London, UK. See https://www.guinnessworldrecords.com/world-records/440880-longest-free-standing-balanced-cantilever (accessed 20/11/2022).

IMS (IEEE Instrumentation and Measurement Society) (2008) *1588-2008: IEEE standard for a precision clock synchronization protocol for networked measurement and control systems*. Institute of Electrical and Electronics Engineers, New York, NY, USA.

Jacobs and Arup (2009) *Forth Replacement Crossing: Environmental Statement*. Transport Scotland, Edinburgh, UK.

Lea F C and Middleton C R (2002) *Reliability of Visual Inspection of Highway Bridges*. Department of Engineering, University of Cambridge, Cambridge, UK.

Li H and Ou J (2016) The state of the art in structural health monitoring of cable-stayed bridges. *Journal of Civil Structural Health Monitoring* **6**: 43–67, https://doi.org/10.1007/s13349-015-0115-x.

McGuill C and Keenahan J (2020) A parametric study of wind pressure distribution on façades using computational fluid dynamics. *Applied Sciences* **10(23)**: 8627, https://doi.org/10.3390/app10238627.

McRobbie S, Wright MA and Chan A (2015) Can technology improve routine visual bridge inspections? *Proceedings of the Institution of Civil Engineers – Bridge Engineering* **168(3)**: 197–207, https://doi.org/10.1680/jbren.12.00022.

Moore M *et al.* (2001) *Reliability of Visual Inspection for Highway Bridges*. U.S. Department for Transport, Federal Highway Administration, McLean, VA, USA.

Ni Y and Wong K Y (2012) Integrating bridge structural health monitoring and condition-based maintenance management. *International Workshop on Civil Structural Health Monitoring, Berlin, Germany*. See https://research.polyu.edu.hk/en/publications/integrating-bridge-structural-health-monitoring-and-condition-bas (accessed 30/11/2022).

Ni YQ, Xia HW and Ko JM (2008) Structural performance evaluation of Tsing Ma bridge deck using long-term monitoring data. *Modern Physics Letters B* **22(11)**: 875–880.

Riches O, Baralos P and Hill C (2019) Queensferry Crossing, UK: durability, maintenance, inspection and monitoring. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* **172(2)**: 175–188, https://doi.org/10.1680/jbren.18.00020.

Romberg M, Brunton K, Wilson J *et al.* (2019) Queensferry Crossing, UK: towers, piers and abutments – design and construction. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* **172(2)**: 126–134, https://doi.org/10.1680/jbren.18.00015.

Sebastian W (2021) Biaxial behaviours of abraded and rehabilitated FRP decks as anisotropic plates under concentrated wheel loading. *Engineering Structures* **203(4)**: 111704, https://doi.org/10.1016/j.engstruct.2020.111704.

Tekin S (2018) *Monitoring System of Suspension Bridges in Turkey.* Ministry of Transport, Maritime Affairs and Communication, General Directorate of Highways, Istanbul, Turkey.

TS (Transport Scotland) (2015) *Interim Amendment 35/15: TS2010 Surface course specification and guidance*, issue 03 edn. Transport Scotland, Glasgow, UK.

Watt D (2017) *Queensferry Crossing: Vision to Reality*. Lily Publications, Ramsey, Isle of Man

Webb G, Vardanega P and Middleton C (2015) Categories of SHM deployments: technologies and capabilities. *Journal of Bridge Engineering (American Society of Civil Engineers)* **20**(**11**), http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000735.

West S, Chisholm A, Oligmuller L, Wharton J and Burbano Pita N (2019) Queensferry Crossing, UK: foundation and geotechnical works. *Proceedings of the Institution of Civil Engineers – Bridge Engineering* **172(2)**: 113–125, https://doi.org/10.1680/jbren.18.00014.

Xu D, Chong H, Main I *et al.* (2019) Using statistical models and machine learning techniques to process big data from the Forth Road Bridge. In *International Conference on Smart Infrastructure and Construction (ICSIC) 2019: Driving Data-Informed Decision-Making* (DeJong MJ, Schooling JM and Viggiani GMB (eds)). ICE Publishing, London, UK, pp. 411–419, https://doi.org/10.1680/icsic.64669.411.

Xu Q, Sebastian W, Lu K, Yao Y and Wang J (2022) Parametric experimental study of ultra-short stud connections for lightweight steel-UHPC composite bridges. *ASCE Journal of Bridge Engineering* **27**(**2**), https://doi.org/10.1061/(ASCE)BE.1943-5592.0001821.

Xua X, Forde MC, Ren Y and Huang Q (2021) A Bayesian approach for site-specific extreme load prediction of large scale bridges. *Structure and Infrastructure Engineering*, https://doi.org/10.1080/15732479.2021.2021953.

Zhang Y, Cardiff P and Keenahan J (2020) A numerical study of the effect of wind barriers on traffic and the bridge deck. In *Civil Engineering Research in Ireland 2020: Conference Proceedings* (Kieran R, Vesna J, Bidisha G *et al*. (eds)). Civil Engineering Research Association of Ireland, Cork, Ireland, pp. 88–93.

Zhang Y, Cardiff P and Keenahan J (2021a) Wind-induced phenomena in long-span cable-supported bridges: a comparative review of wind tunnel tests and computational fluid dynamics modelling. *Applied Sciences* **11**(**4**): 1642, https://doi.org/10.3390/app11041642.

Zhang Y, Cardiff P, Cahill F and Keenahan J (2021b) Assessing the capability of computational fluid dynamics models in replicating wind tunnel test results for the Rose Fitzgerald Kennedy bridge. *CivilEng* **2**(**4**): 1065–1090.

How can you contribute?

To discuss this paper, please email up to 500 words to the editor at support@emerald.com. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions from the civil engineering profession (and allied disciplines). Information about how to submit your paper online is available at www.icevirtuallibrary.com/page/authors, where you will also find detailed author guidelines.