Civil Structures **Workshop**

Report from the First Workshop on NDT, CM and SHM Requirements for Civil Structures

28-29 June 2022

Institution of Civil Engineers, London, UK

BINDT
THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

in collaboration with:
RCNDE ciria i3P

...engineering safety, integrity & reliability

First workshop on NDT, CM and SHM requirements for civil structures

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The civil engineering community faces many challenges in ensuring structures are designed, built and maintained in a safe condition throughout their operational lives. They need to satisfy all the necessary safety and environmental standards, as well as any provisions from the regulators and insurers.

Inspection is crucial to ensuring structural integrity. Often, traditional methods and techniques are used to provide data on the condition of a civil asset. More recently, approaches that are based on non-destructive testing (NDT), condition monitoring (CM) and structural health monitoring (SHM) are being developed and adopted by civil engineering.

The UK Research Centre in Non-Destructive Evaluation (RCNDE), a successful industry-academia collaboration with 20 years' experience, and the British Institute of Non-Destructive Testing (BINDT), a professional engineering institution (PEI), are keen to better understand the requirements of the civil engineering sector for inspection and to explore how research and technology developments in NDT/CM/SHM can support asset integrity in civil structures.

With the support of a cross-civil industry working group, this requirements workshop was convened at the Institution of Civil Engineers, London, on 28-29 June 2022, to capture the industry requirements for NDT/CM/SHM of civil structures. The outputs of the workshop will help guide research and development for the future and further support the adoption of new inspection technologies for civil structures.

Contents

1. Introduction

The Workshop on NDT, CM and SHM Requirements for Civil Structures was designed to bring together stakeholders such as regulators, insurers, designers, constructors and operators with the non-destructive testing (NDT)[1] community to:

- Help the NDT/structural health monitoring (SHM)/condition monitoring (CM) community understand the inspection problems faced by the civil engineering sector;
- Establish the requirements for improved NDT/SHM/CM solutions for large civil structures manufactured from metal, concrete and masonry;
- Consider the application of emerging inspection tools and technologies; and
- Document the specific requirements for action, research or application that will bring about an early benefit in the sector.

To provide focus, the scope of the civil engineering workshop includes bridges, tunnels, retaining walls, culverts and other similar civil structures, but excludes geotechnical assets, railway tracks, roads and pavements, buildings and wet areas. The latter may be the subject of a further requirements workshop at a later date.

It is notable that many civil structures have survived for millennia with a minimal need for inspection, for example the Pantheon in Rome, and yet others have suffered unexpected and catastrophic failure

[1] Note: in this report, for succinctness, the term NDT will often be used to represent the closely related fields of non-destructive testing, non-destructive evaluation, condition monitoring and structural health monitoring.

after just 50 years in service, such as the Morandi Bridge in Genoa, which collapsed in 2018. The long timescales and materials of construction that are typical in the civil sector raise questions that are not often met in other industrial sectors where NDT is perhaps more embedded. For example, how should such structures be inspected and how often? What inspection techniques should be used and what are the thresholds that will trigger an appropriate response? Should sensors be embedded within the structure to monitor for change? If those changes take decades to develop, will those sensors still be functional when needed and will software exist to display and process the data? Will that data even be available when required?

Other questions relate to how the purchaser of a manually applied inspection service can know if the operator is competent to undertake the inspection and if the type of testing is even relevant to the degradation mechanism being experienced. Importantly, who will pay for any improved monitoring of structural assets? Perhaps the designer, because better knowledge about the performance of a structure will allow for leaner and smarter designs and make them more competitive; or the constructor, because the need for rework and the delays that this produces could be reduced; or maybe the operator, who will benefit from a more reliable structure, a reduced number of unforeseen issues and ultimately smaller insurance premiums? Given the long operating life that is planned for most civil structures, it is difficult to understand how the costs can be shared equitably among the various stakeholders so that all parties can benefit, yet there is general agreement that civil engineering would benefit from approaches that are prevalent in other industrial sectors.

This workshop brings together personnel from the civil engineering industry (regulators, insurers, designers, constructors and operators) with personnel from the NDT sector (service providers, research organisations, a professional institute) to explore the above questions. The Construction Industry Research and Information Association (CIRIA) has recently produced some guidance documentation[1,2,3] on the use of NDT for civil engineering and the detection and management of hidden defects in civil structures, so the time is right for bringing the civil engineering and inspections communities closer together. This report forms the main outcome of the workshop and details the presentations and discussions, summarises the requirements identified and defines what success will look like so that it will be clear when or whether the requirements have been met in the future.

Earlier workshops in this series of requirements capture covered wind turbines, aerospace composites, automotive composites, marine composites, heritage railway boilers and Industry 4.0[4].

1.1 Sponsorship and Technical Panel

The workshop was sponsored by the British Institute of Non-Destructive Testing (BINDT), the UK Research Centre in Non-Destructive Evaluation (RCNDE), CIRIA and the Infrastructure Industry Innovation Partnership (i3P).

It was organised by a Technical Panel comprising the following members:

- Robert Smith, University of Bristol, RCNDE and BINDT
- Colin Brett, RCNDE and BINDT
- Leo McKibbins, Mott MacDonald
- Andy Moores, CIRIA
- Jon Watson, Mistras Group
- Will Reddaway, i3P and subsequently East West Rail
- John Moody, BINDT
- Maria Arias, RCNDE.

Of special note was the tenacity of the Technical Panel, which continued with the planning despite the fact that the event had to be cancelled twice due to the COVID-19 pandemic.

1.2 Delegates

The workshop, which was accompanied by a small exhibition, was attended by 54 delegates who represented a wide range of organisations:

Regulator	Office of Rail and Road
Insurance	Marsh Specialty
Owners/operators	East West Rail National Rail Transport Scotland
Constructors	Costain
Inspection service providers/ refurbishment providers	Bachmann Monitoring GmbH Concrete Preservation Technologies Ltd Concrete Repairs Ltd CRL Surveys Ltd Inspectahire Ltd James Fisher Strainstall JME Ltd JR Technology Mistras Group NDT Equipment Ltd Screening Eagle Sercal Stork
Consultants	Mott MacDonald Sandberg Vinci Technology Centre UK
Academic	Brunel University Imperial College London (RCNDE member) University of Bristol (RCNDE member) University of Cambridge University of Exeter University of Strathclyde (RCNDE member) University of the West of England
Research and technology organisations	British Geological Survey The Manufacturing Technology Centre National Physical Laboratory (NPL) TWI
Cross-industry enablers	BINDT (professional engineering institution) CIRIA (industry body) I3P (industry innovation partnership) RCNDE (industry/academic research organisation)

A full list of the delegates is provided in Appendix 1.

1.3 Agenda

The Chair of the workshop, Professor Robert Smith, opened the workshop by outlining the agenda for the two days:

Session 1: Understanding the industry, drivers, business risk, dynamics and tensions

Session 2: Design, failure modes, significance and effect of defects

Session 3: Breakout session on topics raised by Sessions 1 and 2

Session 4: NDT/CM/SHM experiences from the field

Session 5: Potential future NDT, CM and SHM improvements – transfer from other sectors

Session 6: Breakout session on topics raised by Sessions 4 and 5

Session 7: Panel session – key requirements and the way forward.

This report follows the structure of the workshop.

2. Session 1: Understanding the industry

The first session set the scene and consisted of seven presentations made by a variety of organisations that are intimately involved with civil engineering but have different viewpoints. They included a regulator, an insurance brokerage, rail and road operators, a construction company, an engineering consultancy and a university research department. The presentations described a wide range of structures, outlined the main issues that cause degradation and offered views on the inspection and monitoring methods that are deployed, as well as thoughts about how they could be improved to help ensure those assets operate reliably and safely into the future.

2.1 Regulatory viewpoint on the importance of asset information

Steven Dennis, Office of Rail and Road (ORR)

Steven Dennis is the Head of Asset Management at the Office of Rail and Road (ORR), one of several UK Government regulatory bodies, having independent economic and safety responsibilities for Britain's railways and to monitor the performance and efficiency for England's strategic road network. It exists to protect the interests of rail and road users, improving the safety, value and performance of railways and roads, today and in the future. The ORR also regulates the High Speed 1 (HS1) link from London to the Channel Tunnel and provides leadership and expert advice supporting the Channel Tunnel Safety Authority (CTSA) (see Figure 1).

There are six offices in the UK employing about 300 people, spanning engineering, railway safety, economics, competition, statistical analysis and management. Many staff work out in the field, for example conducting on-site inspections across the rail network.

The ORR takes a high-level approach to regulation, guided by the principles of regulatory best practice. It does not seek to mandate policies or standards but ensures that good asset management policies and practices are in place and followed, encourages continuous improvement and innovation, challenges organisations on what data they require to discharge their legal obligations, promotes efficient operational spend and provides constructive challenge to support improvement. It supports decisions that are made on the basis of being risk-based, evidence-based, targeted, proportionate and transparent, ensuring maximum engagement with clients.

Figure 1. The Office of Rail and Road has responsibilities for Britain's railways and for England's strategic road network

Good asset information is perceived as being vital to responsible asset management. For example, the licences that both Network Rail and National Highways operate have a condition requiring them to have appropriate asset information, including information about their condition, capability and capacity. This information must also be readily accessible. However, it is recognised that it is sometimes possible to have too much information or the wrong type of information. The following notes of caution shall therefore be acknowledged:

- Trying to be too accurate in measuring the physical location of large structures when a lower spatial resolution or measurement accuracy would be sufficient;
- An unjustified monitoring/measurement frequency that increases costs and reduces asset availability unnecessarily – asset data must be appropriate and relevant to the needs;
- Asset data not translated into information that the non-expert can understand, devaluing its utility – care needs to be taken to ensure that asset data becomes useful information;
- Models so complex that only a small number of individuals understand how they work;
- Difficulty in understanding an issue and effectively making decisions when one has too much information about that issue;
- Ensuring that those who rely on the information they are receiving understand its limitations;
- Ownership of the system data: intellectual property might not be held by the asset owner, thereby limiting decisions relating to the asset in the future; and
- The financial and environmental cost of storing all the asset information (potentially for many decades).

A further concern is that many structures are old, dating back to the Victorian era or earlier, and full information about their construction and operational duty cycles is missing, if it ever even existed. Structures might also be located adjacent to other structures and degradation of one can impinge on the other. For example, as a result of adverse weather causing erosion, it has been discovered that some rail tracks have been built immediately over the top of old mine workings. As a result, in **most** instances only very partial information is available and key information is frequently missing.

In summary, the ORR is supportive of a balanced and measured approach to asset management, supporting the introduction of new techniques and methodologies and promoting a culture of continuous improvement aligned to ISO 55000[5]. Asset data should be sufficient for the task in hand, being neither so detailed or complex that very few people can understand the message and/or high costs are incurred, nor too sparse that any decisions made are subject to large uncertainties or exclusions. It is also recognised that people will continue to be central to asset management at all its stages, and education and training will have an increasingly important role to play.

2.2 Insurance issues during the construction phase

Adam Davey, Marsh Specialty

Adam Davey represents Marsh Specialty, part of Marsh McLennan, which is a world-leading insurance broker and risk advisor. Although Marsh does not provide the insurance itself, it is able to represent the views and insights of the wider insurance business. It should be noted that this presentation covers activities that take place during the construction phase of a project and not those found when in operation.

Marsh deals with a wide range of civil structures all over the world, including:

- Tunnels, for example the Thames Tideway Tunnel and the Fehmarn Belt tunnel;
- Roads;
- Bridges;
- Viaducts;
- Rail, for example HS2;
- Rail stations; and
- Public structures, for example Heathrow Terminal 5, hospitals, sports stadia, etc.

Risks evaluated include:

- Tunnels collapsing due to the geological ground conditions and the interplay of the key tunnel parameters of depth, diameter and distance;
- Flooding: the general risk of flooding is increasing due to global warming. Tunnel reinstatement costs might be an issue after flooding;
- Water damage: due to pipe breakages in periods of sudden high usage during intervals at sports events, for example;
- Earthquakes;
- Fire: the cladding on residential buildings has received extra prominence due to the Grenfell disaster;
- Wind damage: an example is the effect of wind on a partially constructed bridge; and
- Rail fabrication.

A policy generally covers the period of construction prior to commercial operations. It covers the period of fabrication, manufacture, transit to site, construction, testing and commissioning, but not the operational phase of a project. As well as damage to the asset itself, the policy will also cover third-party damage to third-party properties. Marsh will, however, offer a maintenance defects liability cover period of typically 12 or 24 months to cover physical loss or damage occurring on the project site before commencement.

It is important to differentiate between the terms 'damage' and 'defects'. Damage refers to a detrimental physical change that is unwanted, whereas a defect is simply something that is not right, for example a mispositioned staircase. Damage would be covered by the construction policy but the latter should be covered by the contractor's duty of care or professional indemnity insurance.

A question raised by the audience asked whether insurance premiums could be reduced by, for example, undertaking more thorough examinations during the construction phase to reduce the incidence of some of the deleterious effects due to poor materials and/or conditions that might go on to produce damage during the operational phase. The reply stated that the insurance companies would look favourably on efforts to improve the quality of concrete and steel products, but there was no quantifiable reduction in premiums that could be stated as an incentive. Similarly, a question was raised about increasing the levels of competence in the contractors to improve the overall quality, but the response stated that this is largely under the control of the client.

2.3 Rail owner's perspective

David Castlo, Network Rail

David Castlo is the Network Technical Head at Network Rail, accountable for setting policies, standards and technical strategy, as well as setting the direction of the research and development (R&D) programme. At present, the railway industry is split between the infrastructure manager, Network Rail, and the franchises that operate the services. The creation of Great British Railways in the near future will combine the two roles into one organisation with the intention of simplifying the industry and bringing overall efficiencies.

Network Rail exists to move people and goods where they need to be and to support the UK's economic prosperity. It owns 20,000 miles of track, 30,000 bridges and viaducts, 695 tunnels, 20 major stations and 2500 other stations. The key role is to run a safe, reliable and efficient railway.

As for other industries, there can be no compromise on safety. This leads to a tension between availability (more services) and reliability (keeping infrastructure functioning), whilst keeping within a defined funding envelope. This represents an opportunity for NDT/CM/SHM if asset management can be performed more efficiently than current ways of working whilst maintaining or improving reliability.

The primary way that Network Rail gathers asset information is by using the eyes and ears of teams of inspectors who inspect on a regular basis, prioritising areas where risks are known to be higher (see Figure 2). This has changed little in decades and, of course, will miss several types of hidden risk.

For example, scour, internal separation or hollowness of internal layers, ground voids (perhaps caused by uncharted mining activities) and internal corrosion are all degradation mechanisms that require some form of NDT/CM/SHM for detection and quantification. Hidden construction details and clad structures (for example, many railway arches are tenanted by other businesses) can also place limitations on inspections.

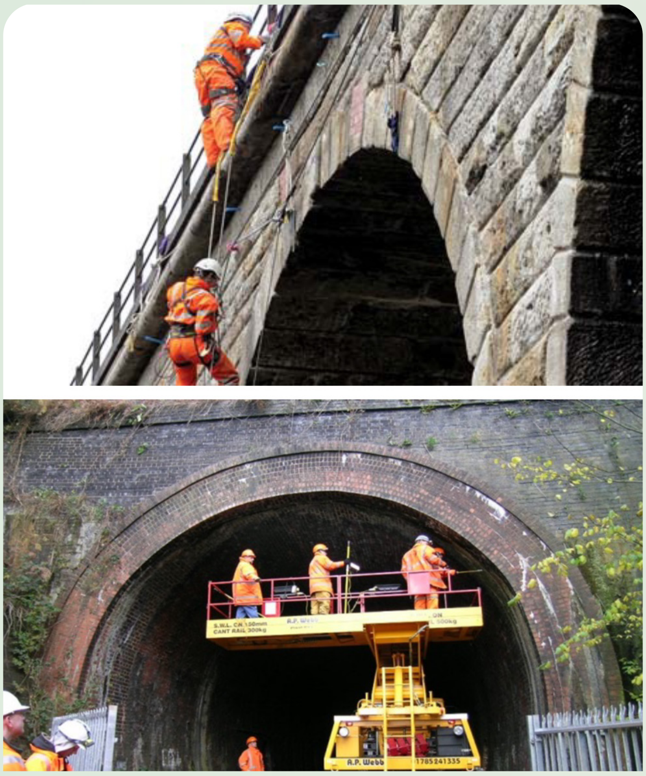


Figure 2. Traditional inspections are carried out using eyes and ears

Changes in earthworks (out of scope of this workshop) represent another area of concern.

To be effective, NDT methods must be simple to use and produce rich information that can be easily understood by non-experts to improve decision-making. However, too much data or a multitude of disparate user interfaces/systems are a potential liability and should be avoided, where possible.

An example of a current initiative that is aimed to improve efficiencies is to automatically inspect tunnels, visualise and share data and use machine learning to prioritise regions where a human inspector should follow-up for a more detailed analysis (see Figure 3). Deployment of this, and similar technologies, can provide an opportunity to learn more about an asset, allowing for refinement of an intervention, hopefully saving money, time and carbon.

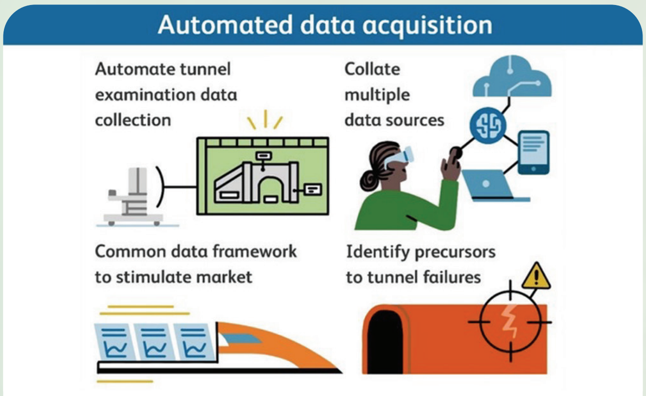
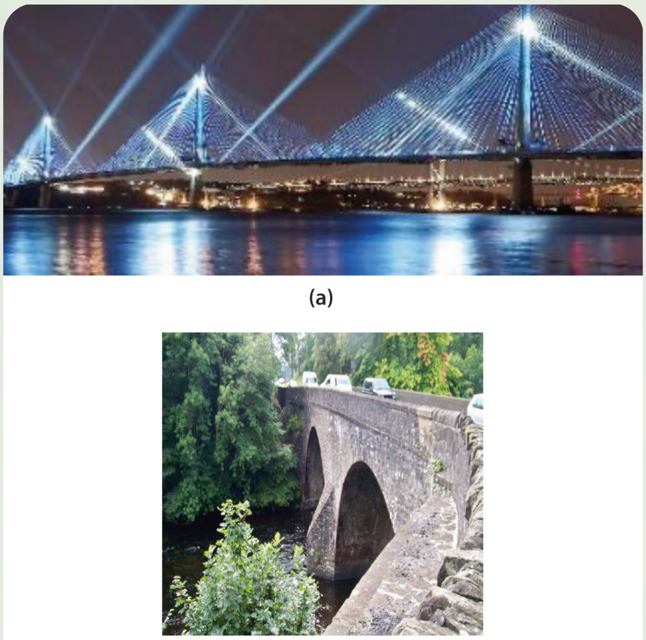


Figure 3. Concept for automated acquisition of examination data for railway tunnels

2.4 Road owner's perspective

Hazel McDonald, Transport Scotland

Hazel McDonald is the Chief Bridge Engineer for Transport Scotland and currently serves as the Chair of UK Bridges. Transport Scotland, the national transport agency for Scotland, is an Executive Agency of the Scottish Government, responsible for road, aviation, maritime, freight, canals, ferries and buses. The road network comprises 5105 structures, 2064 bridges, 694 culverts, 154 footbridges, 964 retaining walls, 749 high masts and 480 gantries. They cover a very wide range of dates: 81% were constructed after 1960 and a small number of new structures are added each year, but the oldest is the A84 Teith Bridge, which was constructed in 1535 (see Figure 4). The majority are simple structures but nevertheless they still require people resource to monitor and monetary resource to invest.



(a)

(b)

Figure 4. The Queensferry Crossing (2013) (a) and the Teith Bridge (1535) (b), illustrating the great range in the ages and complexity of such structures

Typical applications and issues include:

- Scour and redeposition at bridge supports in water, which can be monitored using divers, sonar drones and piezometric sensors. However, sonar has limitations in turbid or turbulent flow;
- Wind management plans for roads and bridges, which are becoming more necessary due to an increasing number of high-wind events. The Forth Road Bridge has been closed to high-sided vehicles 63 times (>50 mph) since the Queensferry Crossing opened in summer 2017. The Queensferry Crossing has only been closed once to high-sided vehicles in September 2018 (gusts >70 mph);
- Fatigue: there is an ageing steel bridge stock, heavier loads and more traffic; therefore, there are inevitable fatigue issues;
- Materials: are we confident of the long-term performance of materials? Are low-carbon concretes sufficiently durable? Are we storing up problems for later?; and
- Vulnerable details: half joints, hinges, post-tensioned elements and hidden critical elements.

Monitoring of structures is usually reactive after a problem has been identified; for example, the displacement and tilt of masonry walls (see Figure 5) and embankments is typically undertaken using remote logging equipment and conditions of concern can subsequently be notified.

(a) (b)

Figure 5. Monitoring the displacement of a masonry retaining wall (a) and manual weld inspection on a larger bridge (b)

More extensive systems utilising weigh-in-motion (WIM) have also been used on larger structures, although there is some concern that it slightly over-estimates loads.

There has been a shift towards a more proactive approach since the closure of the Forth Road Bridge due to a truss end link failure in 2015. An extensive system of strain gauges, load cells, displacement transducers and bearing wear sensors has been installed (over 2000 different sensors), but it can be difficult to interpret the data as the normal or baseline condition is uncertain, so the benefits have not yet been fully realised. An associated issue is that the inspection data often resides in proprietary databases, making access cumbersome and difficult for a non-expert, and there can be a fee to archive this data, which will be essential if it is needed for use in the future. However, some data is available for third parties to use if they want to develop signal processing algorithms, etc, to detect certain conditions.

There have been mixed results when using NDT inspection methods. Hammer tapping is widespread but relies on operator alertness and experience to be effective. Fusion of inspection data originating from multiple methods such as ground-penetrating radar and impact echo is better than either method alone, but there are still concerns about poor resolution, accuracy and repeatability. There have been instances where core samples have been made on the basis of the inspection data only to reveal no problem, leading to doubts about the accuracy of the NDT. Acoustic emission sensors were also installed on the Forth Road Bridge in 2006 to detect potential wire breaks in the main cables, backed up by visual inspection and testing.

At a higher level, it is noted that the asset owner is not generally an inspection specialist and is therefore very reliant on the capabilities of the non-destructive testing/condition monitoring/structural health monitoring service providers for the necessary equipment, software, trained personnel, etc. Guidance on the best approaches to take would be welcomed and some form of training in the basics of the various methods, aimed at asset owners and not the practitioners, would help to remove the barriers to implementation and allow a better dialogue to be achieved between the parties, thereby improving the overall confidence in the usefulness of the results.

2.5 Constructors' drivers, business, risk, dynamics and tensions

Andrew Threlfall, Costain Group plc

Andrew Threlfall is the Head of Technical Assurance at Costain, working in design and construction but having significant experience in operations. The presentation summarised the current or traditional view of civil construction projects and outlined how the industry is changing in an effort to improve the quality and long-term reliability of projects.

Traditionally, civil projects deal with concrete, steel and aggregate materials and often aim for an operational life of 100 years or more; repairs are usually carried out on detecting defects that have the potential to reduce the structural factor of safety to below acceptable limits. There is a high reliance on safety margins that are defined in Codes of Practice, limited *in-situ* testing that is applied sparsely and usually requiring extrapolation to the whole structure, and which can be slow to process to return timely information, and performed using methods that can be subjective in their interpretation.

An example cited is the pouring of concrete, where significant costs and time delays can be incurred if voids are produced that cannot be detected at the time of pouring (see Figure 6). Rework or repairs not only delay the project, incurring extra costs and possibly creating extra health and safety issues that need to be addressed, but can also be very problematic if subsequent construction has reduced the access. Samples of concrete are taken to test the material properties, but results might take 7-28 days to be received and testing *in situ* using a Schmidt hammer to measure the compressive strength is dependent on the expertise of the operator. Furthermore, the repaired structure may then be subject to warranty issues that are associated with the new joint. The Get It Right Initiative (GIRI) estimates that approximately 5% of construction costs are due to defects, equating to about £5 billion in the UK[6].

(a) (b)

Figure 6. The acquisition of samples of concrete (a) and a case of voids produced by incorrect pouring (b)

There are changes already underway that mean the industry needs to be more agile:

- Novel materials and combinations of materials, for example fibre-reinforced concrete, low-carbon cement and basalt rebars;
- More off-site manufacture with on-site assembly;
- Influence of climate change and chaotic weather;
- Increasing complexity of structures and the need to interface with other technical disciplines, for example the construction of smart motorways that include embedded electronics to monitor traffic, etc;
- The emergence of live structural diagnostics;
- Reduced dependence on human interpretation of data; and
- Digital twins emerging from design.

The position that would be good to achieve is one where structures are designed to be inspectable, both during construction and in their operational life, from the outset; the strength/parameters of materials are known with high confidence; improved inspection techniques are developed for hidden defects and/or that are more extensive, and which produce easier-to-interpret outputs; and there is live feedback of the performance of the overall structure so that fault conditions can be dealt with proactively (see Figure 7). A related issue is that there is a need for more consistent identification of assets and their parts, as well as reliable record keeping and archival of information throughout the life of a structure.

It is believed that a willingness to share experiences (as well as risk and expense) will lead to more resilient designs that could challenge the cautious margins that are contained within Codes of Practices and allow performance under 'out-of-code' events such as extreme wind to be determined with more confidence. The benefits would be more predictability (right first time and fewer reactive repairs), more innovation to drive wider industry changes, more connectivity with possible artificial intelligence approaches to develop self-diagnosing structures and, ultimately, enhanced safety during construction and through life. To achieve these goals, it will be important that the insurance companies and clients are involved in order to gain acceptance to any changes that deviate from the status quo.

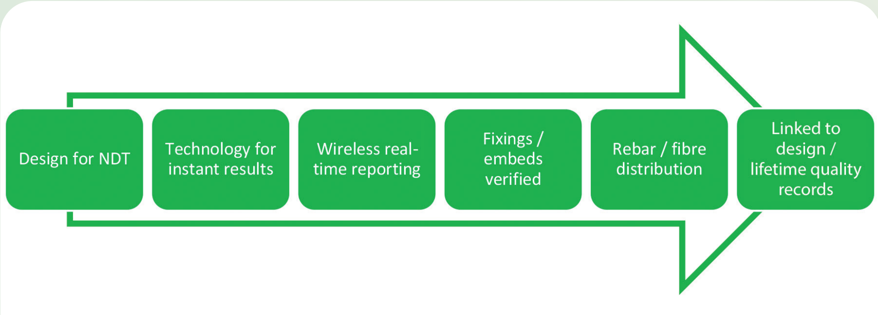


Figure 7. Idealised process for concrete testing

2.6 NDT and CM/SHM: an engineering consultant and designer's perspective

Leo McKibbins and Tim Abbott, Mott MacDonald Ltd

Leo McKibbins is a Technical Director in Civils Asset Management and Tim Abbott is the Bridges Practice Lead within Mott MacDonald, which is a global engineering, management and development consultancy, consisting of 17,000 staff in 150 countries. It has been based in the UK for over 120 years and is one of the largest employee-owned companies in the world.

Mott MacDonald is active in all phases of the life of an asset: from the initial design of a new structure; through providing support during construction; developing management systems, systems and tools during operation; investigating and monitoring arising issues; designing and specifying maintenance and repairs; developing upgrades and life-extension; through to final decommissioning. It is involved in a wide range of structures such as bridges, tunnels, culverts, retaining walls, gantries and so on, and deals with components constructed from steel, brick, stone masonry, reinforced concrete, timber and glass fibre-reinforced polymer materials.

NDT is used in the following four areas (see Figure 8):

- Quality control and assurance in new structures;
- Characterising structures in service;
- Finding defects and helping to plan maintenance; and
- Monitoring to identify change and manage risk.

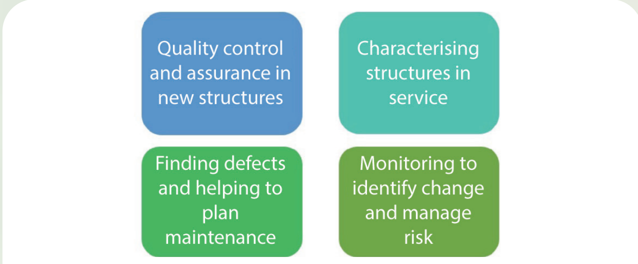


Figure 8. What do consultants/designers use NDT for?

In addition, a further use is often to establish the structural dimensions and material types in structures where the original records are incomplete or missing. This helps to avoid worst case assumptions having to be made about structures.

There is an understanding that improved knowledge about the condition of a structure throughout its life will lead to better maintenance decisions and more robust life predictions and could allow structures to be designed differently without compromising safety, but the use of NDT to further these goals is sporadic. The landscape report produced by the Materials Knowledge Transfer Network in 2014[7] states that, for civil infrastructure, "the use of NDT is neither uniform nor ubiquitous" and "[the civil engineering industry] has been slow to change". Why is this?

An informal survey carried out amongst about 80 delegates at the Bridges 2022 Conference[8] about the perceptions of NDT and where it is used showed that the most common views are that NDT is complex and expensive, but valuable. It is most likely to be used on reinforced and post-tensioned concrete bridges and least likely on masonry and metallic bridges. Figure 9 shows that the three most common barriers cited for not making greater use of NDT were:

- Limited knowledge of NDT;
- Lack of confidence in results; and
- That it is challenging to interpret results.

The most desired problems to be solved included:

- Information about steel reinforcements: geometry, corrosion and strength;
- The condition and integrity of secondary elements (protective coatings);
- The physical condition and composition of concrete;
- Post-tensioning investigation (see Figure 10);
- Measurement of loads/stresses in structures;
- The ability to use NDT in remote locations by a non-specialist, limiting risks to individuals in unsafe environments;
- Accurate measurement of material and weld quality;
- Providing evidence of actual fatigue life left in metal structures;
- Reducing reliance on human interpretation of data; and
- Improving the capability to survey hidden elements.

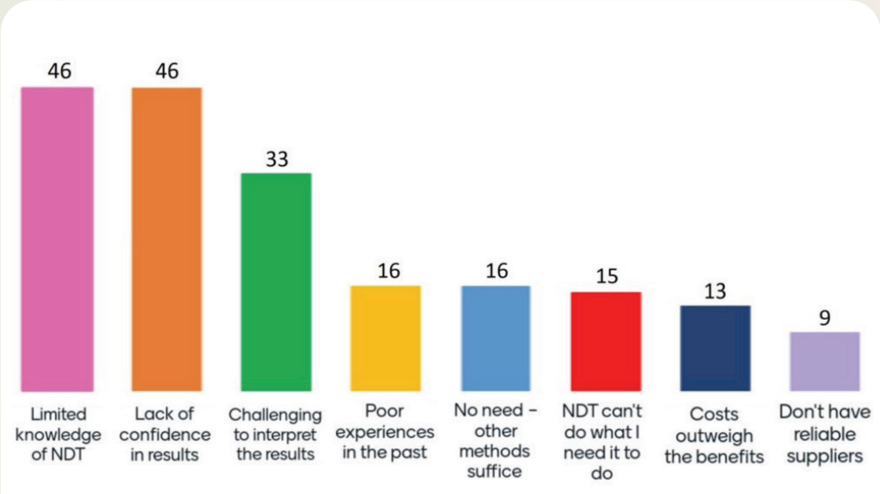


Figure 9. The main barriers to making greater use of NDT

Figure 10. An investigation opportunity is to detect and quantify the voids within post-tensioned cables

Whilst these responses originate from a limited sample, they do echo the objectives stated in the CIRIA C798 guidance[3] that there needs to be an improved general understanding and knowledge of NDT among non-specialists so they can engage more effectively with NDT service providers, opportunities should be identified where NDT can provide value and guidance is needed on good practice in selection, specification, procurement, management, reporting and implementation of results.

In the future it is anticipated that there will be an increasing focus on sweating our existing assets. There will be expectations to use all the tools in the box, go where we have never been before, combining both NDT and monitoring, challenge the codes, adopt risk-based approaches and undertake far more rigorous assessment and analysis. Structures have not always been designed with inspection and maintenance in mind and there will be an increased requirement for unmanned inspection equipment.

2.7 Digital infrastructure (Industry 4.0): case study on railway bridge

Miguel Bravo-Haro, Cambridge Centre for Smart Infrastructure and Construction

Miguel Bravo-Haro is a researcher at the Cambridge Centre for Smart Infrastructure and Construction (CSIC). This organisation is part of the University of Cambridge and is an Innovation and Knowledge Centre funded by the Engineering and Physical Sciences Research Council (EPSRC), Innovate UK and industry. It develops cutting-edge sensing and data analysis models to provide a powerful platform for delivering data to enable smarter whole-life asset management decisions, for both new infrastructure and existing assets. CSIC collaborates with partner organisations across policy, standards and industry adoption to effect transformative change. CSIC staff comprise structural engineers, computer scientists, data scientists and policy makers.

The speaker explained the concept of a 'digital twin' of an asset or system. The intention of a digital twin is to represent reality with a high degree of accuracy so that better and more timely interventions can be made on the real structure and so that its performance can be understood more completely. This, in turn, could lead to subsequent designs being constructed that are more efficient to construct or operate. Ideally, a digital twin combines data, a model and visualisation to create useful information that can be used in real time to achieve these benefits.

An example is the system incorporated within the Cambridge Civil Engineering Building itself. This uses fibre-optic sensors to measure the temperatures and strains in the pipework and key structural elements that provide ground-source heating to the building. The system is used as a research bed to develop sensor technologies, databases and user platforms.

The main case study presented at this workshop concerns an ongoing project to monitor two railway bridges on behalf of Network Rail. The bridges, located near Stafford, carry a range of rolling stock but bottlenecks occur as fast trains often have to slow down to allow goods trains to cross. By instrumenting the bridges, it is hoped to learn how to increase the capacity of the line.

Data relating to one bridge were shown. It is 27 m long and comprises two I-shaped steel girders and a reinforced concrete deck. There are currently 291 fibre Bragg grating sensors installed to measure temperatures and strains across the key structural elements: deck, girders, stiffeners and sleepers. In the next stage, further accelerometers, laser range finders and video cameras are planned to be installed. All these sensors are carefully synchronised with each other.

Live data can be output showing the status of all the sensors, as well as global metrics such as the number of trains passing per day. About 10,000 trains have passed in the last six months and the data allows freight and passenger trains and even a heritage steam locomotive to be differentiated. It has been shown that the utilisation ratio (demand/capacity) of the line at the bridge is only about 10%, so there appears to be significant room available to exploit, possibly by increasing the weight or speed of the trains.

The data can be mined more deeply to extract the positions and weights of each axle of any train as it crosses the bridge. This information could, in principle, be used to optimise the train loading models for the structure. Also, as a train leaves the bridge, the natural vibration frequency and the critical damping ratio can be determined. Changes in these parameters are potentially indicative of damage in the bridge, but probably only to gross changes, although the sensitivity should improve as more experience is gained.

The exercise will allow knowledge to be gained about the number of sensors that are needed to produce useful results. Clearly, as more sensors are installed the cost increases, but what is the smallest number that can sensibly be used and how much redundancy against failures is recommended? It is anticipated that guidance will result so that installations on other types of bridges can be optimised. A further challenge is to develop standardised procedures for the construction of digital infrastructure that will remain valid for what could be several decades before any problems emerge.

Ultimately, a greater understanding of the behaviour of key infrastructure will allow designers to incorporate changes into the next generation of designs and operators to then optimise their usage, thereby producing benefits to society.

3. Session 2: Design, failure modes, significance and effect of defects

The second session provided an overview of the range of inspection and monitoring methods that are currently used for civil structures.

3.1 Review of failure modes and inspection methods

Adrienn Tomor, Brunel University, London

Adrienn Tomor is a Senior Lecturer at Brunel University with a background in bridge engineering. This session provides an overview of the forms of damage that occur within metallic, concrete and masonry structures, as well as a review of the possible inspection and monitoring methods that can be used to detect, measure and characterise that damage.

3.1.1 Metal structures

There are three main issues causing degradation relating to metallic structures:

- Structural de-stress;
- Corrosion; and
- Accidental or deliberate damage.

As an example, bridges can collapse because of buckling of plates that are too thin to support the required loads. In principle, deformation might be observed at an early stage if the structure is monitored regularly.

Load cycling may initiate and propagate fatigue cracks, most often at stress concentrations such as a bridge pedestal or where roller bearings have seized. Such cracks might be observable at an accessible surface but could be hidden underneath the surface.

Galvanic corrosion occurs where two or more metals come into contact in an electrolyte. The more reactive metal acts as an anode and the less reactive a cathode; the electro-potential difference between them causes the anode metal to corrode preferentially. Selection of similar metals will reduce the effect in new builds, but the issue could be already present in older structures.

Pitting corrosion on a surface is another potential problem.

Fire damage can cause significant weakening of bridges because steel can lose half its strength at temperatures higher than 500°C. This effect might not be obvious visibly.

There are many inspection methods that can be applied on metallic structures, many of which are described in CIRIA C664[9]. Table 1 provides a summary.

3.1.2 Concrete structures

The key issues for concrete structures are:

For reinforcement deterioration:

- Water penetration;
- Carbonation; and
- Chloride attack.

For concrete deterioration:

- Alkali-silicate reaction;
- Sulphate attack; and
- Frost attack.

Water penetration can lead to corrosion of any internal rebars, which in turn can lead to spallation and/or delamination of the concrete itself.

Carbonation occurs when carbon dioxide from the atmosphere has penetrated concrete. This is benign until it reaches the internal steel, where corrosion can be initiated. A phenolphthalein solution can be sprayed on to the surface of the concrete to detect its presence; if there is no colour change then carbonation has already started.

Chloride attack is usually due to seawater or the ingress of de-icing salt. This breaks down the passive film around the internal steel so corrosion initiates.

Alkali-silicate reaction, otherwise known as 'concrete cancer', is due to the ingress of water, which causes sodium silicate to form. This then swells, causing loss of strength of the concrete.

Sulphate attack is visible as a white powder on the surface and can be mitigated by using Portland cement.

Frost attack is due to the ingress of water at crevices and expansion joints, etc.

The main inspection methods are listed in Table 2. Note: strain gauging, fibre Bragg gratings and accelerometers, shown in Table 1, are also relevant to concrete structures.

3.1.3 Masonry structures

The two main issues are:

- Water ingress; and
- Cracking of mortar.

Water damage may be caused by water breaching a waterproof layer, which may then cause deformation or other problems, including washing out of mortar. Water can also enter through cracks in mortar, which is more likely when the mortar is stiff and inflexible. The freezing and thawing cycle is a common cause of cracking in mortar.

Table 1. Inspection methods for metallic structures

Inspection method	Principle and usage
Liquid penetrant testing (PT)	A dye or ink is sprayed over a surface, which can be ferritic or non-ferritic. If a surface-breaking crack is present, some ink will be drawn into it by capillary action. When the excess ink is removed, the positions and lengths of cracks can be seen.
Magnetic particle inspection (MPI or MT)	Only suitable for ferritic materials. An applied magnetic field and a solution containing iron filings reveal the position and length of a surface-breaking crack. Quicker to apply than PT.
Eddy current testing (ET)	An electrical method useful for tracing hairline cracks that are difficult to see.
Hardness testing (HT)	Measures the toughness/hardness of materials. A non-destructive measurement can be made using a portable instrument for field use that bounces a small ball bearing off the surface and the recoil velocity relates to the hardness. If a sample is removed for the laboratory, then an indentation test can measure the Vickers hardness. These measurements can give a measure for the maximum stress before the onset of plasticity.
Charpy test (destructive)	The yield strength of a material can be measured using a standardised V-notch impact test on a sample removed from the structure.
Strain gauges	Strain rosettes or linear voltage displacement transducers (LVDTs) can be used to measure local displacements or deformations in the surface.
Fibre Bragg gratings (FBGs)	Optical fibres can be installed to monitor strains at several points over large distances.
Accelerometers	The dynamic response of a structure can be measured using installed accelerometers. Fourier transforming to the frequency domain gives a spectrum that can be analysed to detect stiffness changes over time. Temperature can also cause frequency shifts, so a baseline is needed as a comparator.
Acoustic emission (AE)	A distribution of acoustic sensors listens for the pulses of sound that occur when a crack grows and triangulation amongst the sensors can provide the location of the source. Other effects, such as two surfaces rubbing against each other, can also produce sound energy, so filtering is used to screen out irrelevant signals. A few sensors can cover a large structure.
Ultrasonic testing (UT)	A versatile method that can find and size defects on the surface and subsurface, as well as locations that could be difficult to access. In its simplest form, it can be used to measure component thicknesses, including the thickness of paint coatings.
Holiday detection	The presence of through-holes in painted or coated layers can be detected using a holiday detector. This applies a voltage across the layer and reacts to a conductive path, if present. A pull-off test can also be used to check how effectively the paint is adhered.

Table 2. Inspection methods for concrete structures

Inspection method	Principle and usage
Visual testing (VT)	The most important method, but it needs to be performed in a systematic way to be effective. Can be coupled with metrology to measure deformation of arches, for example.
Borescopy/endoscopy	Rigid or flexible light guides can be used to view internally and around corners that prevent line-of-sight. Can be used to check for the presence of grouting in post-tension ducts. Coring may be performed to provide access.
Schmidt hammer	A portable device that measures the rebound energy of a spring-loaded mass impacting against the surface of a sample. Used for delamination surveys. Can also be used to infer the presence of carbonation.
Electrical resistivity	Relates to the rate of corrosion, not the absolute value.
Moiré pattern gauges	Moiré crack monitors can be used for measuring movement between two items, typically between two sides of a crack in a concrete surface. Submillimetre displacements can be observed. Permanently installed monitors can be viewed from a distance via a camera.
Ground-penetrating radar (GPR)	Can detect the depth and spacing of rebars in concrete. Resolution worsens with depth.
Ultrasonic velocity	Measures velocity changes due to different types and densities of concrete.
Ultrasonic testing	As for metals, to detect voids and cracks, although lower frequencies have to be used, which compromises resolution.
Thermography	An infrared camera can detect and record anomalous temperature distributions that might indicate an underlying problem. The decay of temperature with time can be used to infer positions of delaminations. The field of view can be large, enabling large structures to be imaged.

Repointing with the wrong mortar, for example cementitious mortar, can lead to cracking. Horizontal earth pressure at retaining walls can also lead to deformation and cracking. Ring separation of the arch from the stiff spandrel wall can be a big issue for masonry bridges.

Table 3 provides an overview of the main monitoring methods for masonry structures.

3.1.4 Polymers and composites

Polymers and composites are starting to be used to strengthen structures such as bridges. Plates made from carbon fibre-reinforced plastic (CFRP) are used to stiffen structural sections of concrete or steel, while fibre-reinforced plastic (FRP) is flexible and can be wrapped around beams, newly cut openings, columns, pre-stressed tensioning parts, etc. These materials present new inspection challenges.

4. Session 3: Breakout session

A breakout session was held at the end of Day 1 in which all the participants were invited to contribute to five separate topics before reconvening to review all the responses. The five topics were to consider the non-destructive testing, condition monitoring and structural health monitoring requirements that relate to:

1. Ownership drivers;
2. Contractor drivers;
3. Design drivers;
4. Design, failure modes and the effect of defects; and
5. Solutions to the challenges identified.

The summary of responses is given in Table 4.

Table 3. Inspection methods for masonry structures

Inspection method	Principle and usage
Compressive strength of bricks	The compressive strength of bricks can be measured using a dedicated testing machine in the laboratory. This can be used to check the load-bearing capacity before use in construction. Older bricks from 1770-1830 might have a compressive strength of 20 N/mm^2 and more modern bricks up to 80 N/mm^2.
Flat-jack testing to measure local loads	The loads that are present within a masonry wall can be tested using flat-jack testing. Two pins are inserted into the wall to give a reference distance. Two slots are then cut into the wall between the pins to relieve the load locally, which causes the distance between the pins to change. The gap is then pressurised with oil and the distance between the pins is monitored until it returns to the initial separation. The oil pressure needed to achieve this gives a measure of the local load in the wall.
Deflection and distortion monitoring	Using strain gauges, linear voltage displacement transducers and Moiré tell-tales, as for other materials.
Digital image correlation	Detailed comparison between multiple visual images to quantify local displacements at the surface that can be indicative of underlying problems. Can survey large areas.
Acoustic emission	As for metallic structures. Can be used to indicate active areas in railway bridges.
Accelerometers	For dynamic and general loading, as for metallic structures.

Table 4. Summary of responses to the breakout session on Day 1

Topic 1: Ownership drivers and NDT, CM and SHM requirements
• There were concerns raised relating to the knowledge and expertise of the NDT operator. How does the owner know if the operator is competent and doing the job well? How does the owner know if the best technique is being used? • This requires someone working for the asset owner to specify what is needed and where to carry out the inspection and define what they are looking for. Ideally, there would be in-house expertise to guide the operator (intelligent client), but it is recognised that this is not always the case. • Alternatively, there needs to be wider knowledge and use of independent NDT advisors for companies that do not have in-house expertise. • It was suggested that some percentage of structures could be monitored in a preventive way to gauge the performance of a larger population of structures. They could also be used as a reference standard for the future. • Owners want the data **and** the interpretation of that data in terms they can understand. • Owners want safety, consistency across time and long-term relationships with suppliers, preferably avoiding using different providers, which might prevent mapping or trending. • Owners would like more collaboration to share costs and risks, for example when trying a new technology, and to develop a greater understanding of the validity of inspection methods. However, they do not want to be a research project or the guinea pig for a trial. • What is SHM and what can it do? Owners do not fully understand what it can do and how it differs from CM. Work is required in defining SHM and explaining how it can be applied to get good value.

Table 4. Summary of responses to the breakout session on Day 1 *continued*

Topic 2: Contractor drivers and NDT, CM and SHM requirements
• Insurance for contractors is very important. Could better use of NDT/CM/SHM increase their confidence and reduce the risk? • An insurance retainer could help drive the introduction of better whole-life monitoring. • Contractual costs *versus* value for the asset owners. Contractors need to be more open about their errors and the costs that errors create. • There are tight margins, so there is a very small overhead available to invest. • Many inspection requirements are added at a later time, often as post-contract add-ons, and sometimes cause disruptions. This needs to be brought in at an earlier stage. • Lack of education of what NDT/CM/SHM can do. Contractors will become upskilled if they are better educated on NDT/CM/SHM. • Avoid rework, as it is this that reduces the profit margins. Early monitoring could help with this but also with needing less time to build, needing fewer materials, increasing efficiency, reducing waste and emissions and ultimately generating money for the contractor. • How can inspection work be verified independently to check relevance and quality? • Some data is useful for the contractor but perhaps not for the client – they do not see the value of it.
Topic 3: Design drivers and NDT, CM and SHM requirements
• Intelligent use of NDT/CM/SHM could lead to a reduction in conservatism and hence a reduction in the cost of ownership and operation. Adherence to codes is a safe, no-blame island for designers. However, new/innovative approaches introduce risk – who owns that risk? It is noted that the organisation who owns the risk is not always the organisation who owns the benefit. Aligning risk and benefit is difficult but necessary. • Does improved monitoring mean less robust structures? Can you get the same safety and the same speed of construction for smaller costs? • Design for inspection: what benefit does it provide to those involved in the design and construction process? If the designer/constructor does not buy in, it will not happen. Clients need to make clear those requirements and bring this conversation up as soon as possible (intelligent client). • Design for manufacturing assembly (DFMA). This relies on customisation of the process; again, it all comes down to introducing changes to codes, *ie* managing innovation and risk while maintaining safety. • Move to a more probabilistic design process to remove some conservatism; design for specified reliability levels depending on the criticality of the structure. This is going to require a great deal of data and analysis to understand it, with better sharing of risks, and it would require everyone to buy into a new approach to doing things. • Value of the data and who owns it? Can data be used to provide benefits to the designers to refine their processes? If the data was open and all designers could access it, it would bring their prices down, therefore benefiting the asset owners. • The industry needs to move towards more whole-lifecycle thinking from the very early stages of specifying an asset.
Topic 4: Design, failure modes and effect of defects – NDT and CM requirements *How can NDT/CM/SHM be targeted to bring early benefit?*
• Having a strategy from the outset; an appreciation for what could happen and what the plan and the objectives are. Identifying this early would be beneficial. Be prepared rather than reactive. This needs a thorough understanding of the structure, material, damage mechanisms and thresholds. • Identifying the value in the saving, either in maintenance, repair, structural use, greater life extension and usability, etc, could enforce or demonstrate the benefit of having a strategy. • Early involvement of designers, constructors and operators to contribute to the selection of relevant NDT/CM/SHM. • Risk-based inspection – need better understanding and modelling, *ie* database and trend analysis of individual structures but also large populations of different structures. Share relevant information across industry. • React to potential issues earlier through smarter monitoring of structures. • Need better understanding of the criticality and severity, but also the position of defects could affect the way that NDT is deployed. Optimise the implementation of NDT. • Upfront investment in additional testing to reduce expenditure later when access can be poor. • 'Be bold and try' – more innovative approaches could create unique data and insights into the performance of a structure. Small investments could generate more useful knowledge than large installations that are unfocused. • Environmental factors. There needs to be better appreciation of the effects of environmental change, for example the presence of water in structures, poor drainage, etc. • The capability to extend lifetime assessments would bring early benefits.

Table 4. Summary of responses to the breakout session on Day 1 *continued*

Topic 5: What would solve the challenges identified? *What would characterise the solutions?*
• Understanding all the stakeholders and the wider context – there are many NDT/CM/SHM solutions out there; how can they be adopted in the civil sector? How do we make them applicable, taking them out of the laboratory and applying them to real problems? What is the value of these solutions? • The financial justification is key. What is the value of the data (and to whom) and the role of insurance? **Data** • Turning the data into useful information. Maintaining the fidelity of the data (not corrupted) if it is open source. Sharing of data to learn collectively? • There are some barriers to communication and interpretation of data, especially when proprietary systems are used. • Owners cannot be expected to understand the data at the same level as the NDT service provider and should not need to. However, the key messages must be clear and concise. • Who owns the NDT data? Who pays for its long-term archival? Who performs trending analyses? • Can approaches based on artificial intelligence and machine learning be trusted? How can such an approach be validated? **Technology** • Sensors need to be very reliable, especially if mounted on/in a structure for several decades. • The pace of technology is recognised as a potential issue. Will expertise, equipment and software be available and/or useful when it is required? • Accuracy, resolution and depth of penetration of NDT/CM/SHM methods needs to improve. Developments that are driven by civil engineering requirements would be welcomed. • There needs to be a better understanding of the benefits of embedded *versus* mobile sensors. • How can NDT be integrated into a structure? • Could monitoring via satellite or drones offer a more cost-effective method (for some structures)? • Does monitoring provide a sufficiently reliable early case for intervention? • Move towards a more preventive and proactive strategy; less reactive to incidents. • How to validate artificial intelligence and machine learning approaches to data analysis? **Training** • Training, awareness and upskilling of the workforce in general. NDT technologies currently considered to be a black box but industry needs greater ownership. • Human factors and the role of the engineers: there is a big reliance on visual inspections in the civil sector and time pressure on operators to do the job quickly. Technology could improve safety of inspection personnel. • There needs to be a greater understanding of the accuracy and resolution of NDT/CM/SHM methods. • There needs to be NDT training available that is specific to civil engineering issues, for example in concrete inspection. • Civil-specific operator certifications are needed, for example an ISO 9712-compliant scheme such as PCN. Limited schemes already exist, for example the Bridge Inspection Certification Scheme (BICS) run by LANTRA, but this needs to expand. Aim for standardisation across the sector and inter-sector.

5. Session 4: NDT, CM and SHM experiences from the field

Session 4 presented the experiences from the field of a variety of inspection service providers.

5.1 NDT/CM/SHM service provider's perspective

Jon Watson, Mistras Group

Mistras is a large provider of NDT/CM/SHM services. As a civil engineer and expert in NDT and SHM, Jon Watson's focus is solving civil engineering problems specifically in the asset management of bridges.

Including NDT and SHM in a good asset management plan is key to maintaining the structural integrity of bridges and other structures.

Unfortunately, failure in service does occur, one such being the collapse of the Nanfang'ao Bridge in Taiwan in 2019 (see Figure 11), having only had one inspection in its 21 years of life. This lack of inspection meant critical defects in the cables were missed, causing an overestimated integrity of the cables, which led to the catastrophic collapse of the bridge.

The Morandi Bridge in Genoa suffered a similar fate after 51 years in service (see Figure 12), killing 43 people in August 2018.

In contrast, an example of a successful asset management plan is the structural health monitoring of the Hammersmith flyover in London. In 2011, a cable break was detected using acoustic emission sensors, which led to the closure of the bridge and its subsequent repair. Thus, a catastrophic collapse similar to that of the Morandi Bridge was averted. A robust SHM acoustic emission system was installed and continues to be in place and monitored.

Figure 11. The Nanfang'ao Bridge, Taiwan, collapsed in 2019

Figure 12. The Morandi Bridge, Genoa, collapsed in 2018

For the Queensferry Crossing across the Firth of Forth in Scotland, the installation of sensors was conceived at the design phase and a structural health monitoring system was put in place to ensure asset management through life.

It is important when planning SHM or NDT of a structure to understand what information is already available from previous records. What do you already know and what do you need to find out? How has the structure behaved in service and where are the critical defects likely to be located? Detecting voids using impact testing, determining thickness using ultrasonic testing and determining the maximum strength are all part of the initial assessments and inspection.

Key aspects for successful deployment of NDT/SHM are having competent people, the appropriate NDT equipment and system, relevant test samples and a robust process (see Figure 13).

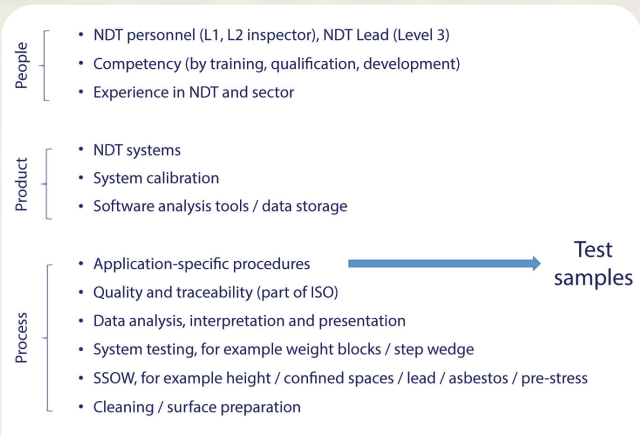


Figure 13. Success elements in NDT/SHM

Test samples are key for developing a technique and to determine the probability of detection (POD), resolution and repeatability. They also help to ensure that inspectors are trained and can be used to provide a demonstration to clients for on-site quality assurance.

Solution-based NDT and SHM will increasingly become a standard part of an inspection and assessment tool kit for bridges and other structures. Along with other complementary methods, this will result in improved asset management and reduced risks and enable the life-extension of structures. As digitalisation progresses, the resulting enabling technologies will support asset management into the future.

5.2 NDT supply chain perspective – concrete testing

Shirley Underwood, Screening Eagle Technologies

Through its global network, Screening Eagle offers comprehensive inspection solutions for civil structures. It was founded in 2019 from the merger of Proceq, a Swiss company leading in NDT sensors since 1954, and Dreamlab, established in 2015 in Singapore, bringing expertise in software and robotics.

From an NDT supply chain perspective it is important to "Act early, be smart, don't procrastinate and be too late!" Preventive inspections drive actionable maintenance and allow structures to 'age gracefully' (see Figure 14).

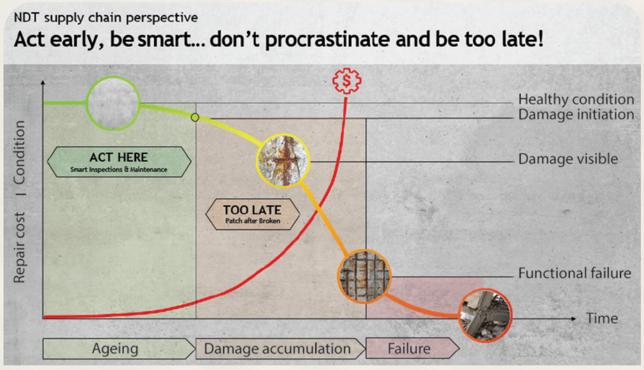


Figure 14. Supply chain perspective

Maintaining the health of concrete is imperative to ensure it:

- Is dense, strong and uniform;
- Has the correct compressive strength;
- Has rebars in the right place; and
- Has no delaminations, voids, honeycombing or cracks.

Quality-controlled construction is a must and 'birth certificates' (plans with all defects marked) should be kept as a record; regular visual inspections, including NDT, should be completed to ensure integrity through life.

Concrete can be inspected using ground-penetrating radar (GPR) and pulse-echo ultrasonic testing (see Figure 15). Heat maps can identify 'hot-spot' areas for further investigation.

Preventive structural inspections focus on three things and an analogy can be made with the medical industry (see Figure 16).

As can be seen in Figure 16, there is no single technology that will address all inspection requirements; a multi-technology approach is a requirement to ensure the integrity of concrete.

Healthy structures are more environmentally friendly and boost net present value.

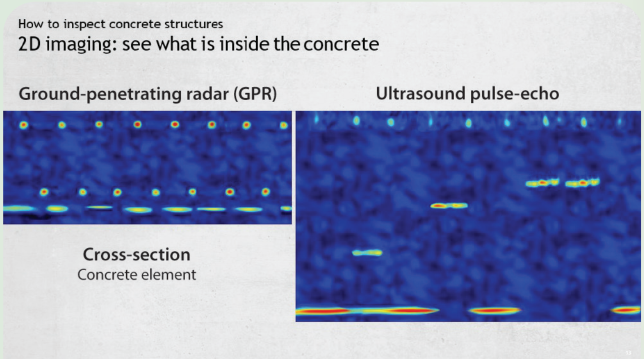


Figure 15. Examples from inspection of concrete showing 2D imaging from GPR of rebars (800 mm depth) and pulse-echo ultrasonic testing showing delaminations (2 m depth)

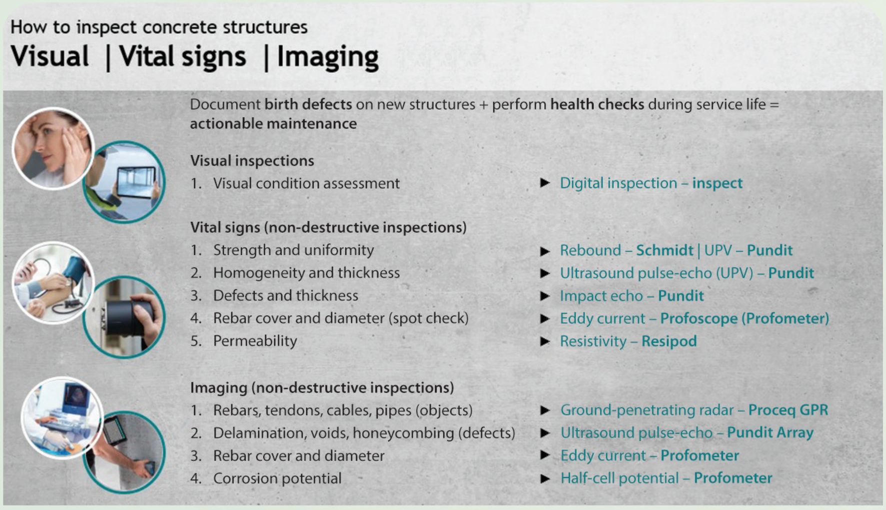


Figure 16. How to inspect concrete using analogies from the medical industry

5.3 Examples in monitoring and load testing for civil asset management

Dave Cousins, James Fisher Strainstall

Dave Cousins is the Principal Engineer for Bridge Engineering at James Fisher Strainstall, with a focus on monitoring for civil structures.

There are various ways in which monitoring can be applied, including asset monitoring, load tests, during construction or temporary works, for *in-situ* stress tests and throughout the lifecycle. It should be noted that monitoring systems can be affected by the weather conditions and particularly by temperature.

In SHM, data related to civil infrastructure is observed and measured. It can be more easily installed early after construction and then monitored in service throughout life.

Load testing is the use of structural monitoring for short durations, observing responses to controlled or measured actions, for example a truck crossing a bridge.

Examples of approaches to monitoring and load testing include:

- **For construction or temporary works**
  Works may affect the stability or performance of a new or existing asset. Trigger levels and rectification actions need to be set. An example is the Klais Organ in Bath Abbey: during replacement of a beam beneath the organ, monitoring ensured no disturbance.
- **Asset monitoring**
  Data platforms gather data from multi-sensory systems and then process and analyse the data, providing outputs that allow visualisation, comparisons, alerts and reports. During monitoring, it is essential to measure temperature and weather conditions to disprove that temperature is the cause of any issues. Outputs need to be simple and understandable by the asset owner. An example is the Queensferry Crossing, near Edinburgh (see Figure 17): an SHM system was designed and 2184 sensors were installed during build. Using live display screens, Transport Scotland has the ability to monitor the bridge condition.
- **Investigations**
  Is there a problem? Does it need further investigation? Is there a need to prioritise maintenance? One example involves the Mollison Avenue bridge bearings: visibly over-displaced bearings were investigated for their temperature response over 48 hours. This was with a high sample rate to detect vehicle loads. Analysis suggested the likely cause was abutment settlement.
- **Numerical assessment**
  Assessment quantifies the functional capacity. Load tests can compare the true stiffness and stresses against a finite element analysis (FEA) model. An example is the A52 Clifton Bridge in Nottingham (see Figure 18) where post-tensioning had deteriorated. Stress measurements were made in post-tensioned wires though the anchorage was not accessible.
- **Responsive mode**
  A fault that has already occurred or a risk that has been identified can invoke a need for monitoring. An example is flood monitoring for Network Rail: five bridges in Wales and the West were monitored with ultrasonic sensors and cameras. Department for Environment, Food and Rural Affairs (DEFRA) flood warning displays were integrated for enhanced monitoring of the bridges.
- **End of life**
  Monitoring for condemned structures when decommissioning is not immediately possible and life extension is required. Trigger levels and automated alerts are required, for example, in a rail bridge, monitoring using wireless track tilt sensors on the superelevated bridge section extended the life of the structure by twelve months.

The following are identified as 'pain points' for civil engineers, which should be considered:

1. Selecting specialist suppliers;
2. Analysis and interpretation – factual reports, 'black box' common methods, understanding, standards (NDT);
3. Trigger levels and implementing actions; and
4. When is testing or monitoring required?

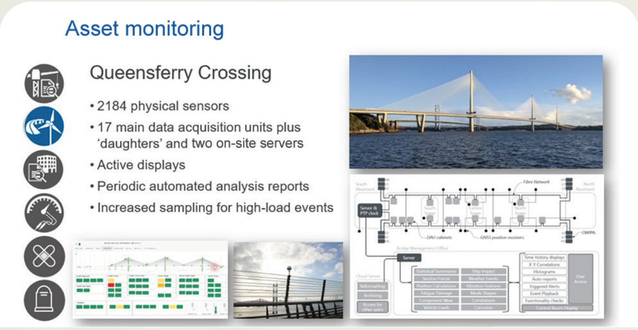


Figure 17. Active monitoring of the Queensferry Crossing, Scotland

Figure 18. The A52 Clifton Bridge, Nottingham, underwent the assessment of post-tensioned wires using stress measurement

5.4 An engineering consultant and designer's perspective – case studies

Tim Abbott and Leo McKibbins, Mott MacDonald Ltd

NDT is used by engineering consultants and designers for:

- Quality control and assurance in new structures;
- Characterising structures in service;
- Finding defects and helping plan maintenance; and
- Monitoring to identify change and manage risk.

Case studies

- **Yetminster Bridge**
  Fatigue in metallic bridges is a known issue. To better understand this, some research has been completed with the University of Surrey on the Yetminster Bridge. The work started with a desktop study before the bridge tear-down and a section was taken to the University of Surrey for analysis of fatigue and to gain a more comprehensive understanding of the mechanisms and monitoring required. Acoustic emission was already being trialled for crack propagation. The desire was to use NDT and SHM methods *in situ* on metallic bridges more widely in the future.
- **Hammersmith Bridge**
  This is a Grade 2* listed chain link suspension bridge over the River Thames. A study of the bridge's condition and integrity, including the paint, was completed using visual and NDT techniques and the results determined that a bridge pedestal had cracking. It was probable that the cracks were initiated during manufacture and that in-service stresses had caused the cracking to grow. The bridge was closed to traffic and subsequently to pedestrians and river traffic. Acoustic emission and temperature sensors along with strain gauges were installed to monitor the bridge, which allowed it to be reopened.

Problems: using ultrasonics to inspect cast iron was highlighted as an area that Mott MacDonald would like to further investigate to understand defect types. Initiating a project in this area will help predict the life of structures.

5.5 NDT of civil structures in the nuclear power industry

Phil Pearson, Consultant

With 37 years' experience in the nuclear industry, Phil Pearson presented a personal perspective of nuclear safety-related structural integrity and the need for advanced NDT to support the civil nuclear structures and future civil/structural infrastructure integrity. His background includes the design and build of pressurised water reactors (PWRs) and advanced gas-cooled reactors (AGRs), civil reactor structural integrity and experience working in nuclear submarine shipyards and dockyards. Phil is a Fellow of the Institution of Structural Engineers (IStructE).

The care and maintenance of a nuclear reactor (termed a 'safestore') continues long after its shutdown for over 90 years to allow for radioactive material decay. Reactor building safestores create a challenge to maintain long-term structural integrity in structural form/buildings surrounding the nuclear reactor. For Magnox reactors, the original anticipated building life was 25 years (40+ years for AGRs). Magnox reactors generally had an extended operating life to 35 years and beyond, much longer than planned (see Figure 19).

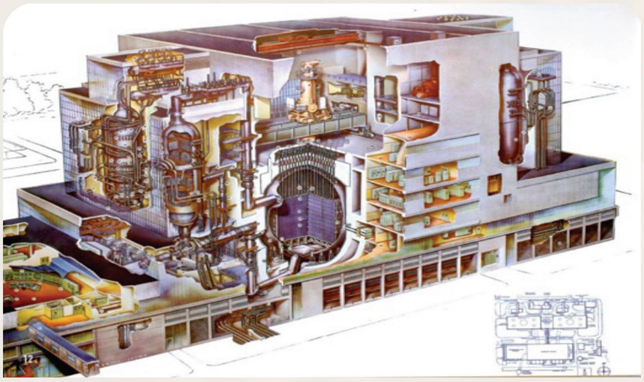


Figure 19. Dungeness A reactor, bioshield and structure

NDT is a valuable tool across all civil and structural engineering integrity (including highways, dams, docks, national infrastructure), not just civil nuclear sites. The inspection of these heavy civil engineering (ie generally reinforced concrete (RC), but equally relevant to masonry or earth dams) structures poses considerable challenges for NDT, including:

- Ageing concrete assets, including the pre-stressed concrete pressure vessel (PCPV), bioshield concrete, the safestore (*ie* around the reactor and boiler), water retaining cooling ponds;
- Challenging environments – inaccessibility, higher radiation dose areas;
- Buried structures and ground conditions;
- Extended life and/or decommissioning nuclear installations;
- Pressure vessels (for example steel supports);
- Long-term effect of high thermal stresses on structures; and
- Nuclear safety (NS): justification on long-term structural integrity of operating or decommissioning sites. Not just the effects of the wet-dry cycle (for example chloride corrosion of RC structures).

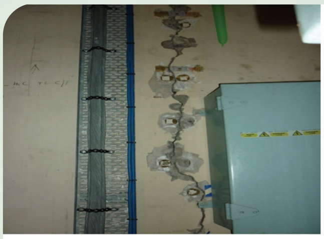
As part of its Licence Conditions (LCs), a Nuclear Licenced Site has to meet LC28 and ensure that "all plant which may affect safety must be subject to regular and systematic examination, maintenance, inspection and testing (EMIT)". Most importantly, a nuclear operating site must ensure any NDT will not influence or affect essential electrical control systems.

To ensure structural integrity, can NDT identify:

- Corrosion (*ie* reinforced concrete or embedded metal at depth, such as rock anchors or pre-stressed tendons);
- Ageing mechanisms or defects in concrete (for example variation in density, delamination, crack depth); and
- Water ingress, including that potentially caused by radiological damage to water bars?

Ultimately, could NDT become a supplementary tool in the assessment of residual design capacity, to extend design life or aid dismantling/decommissioning?

In a nuclear reactor environment, concrete ageing and the presence of defects are an issue (see Figure 20). Some of the causes of concrete degradation could have been initiated from construction practices used in the 1950s and 1960s and exacerbated from environmental conditions during operation.



Significant ~6 mm tensile thermal cracks.

Depth of bioshield wall ~2.1 m.

The depth of the crack is unknown (NDT trials undertaken in 1998 were inconclusive (c/o CETWG – Pearson)).

(a)

PC beam bearing support in the bioshield wall underwent a brittle failure due to thermal cyclic ratcheting and beam rotation caused by differential settlement.

NDT tests were used to determine the depth of surface delamination. Limited depth (*circa* 1998).

(b)

Figure 20. Examples of structural distress in concrete: (a) thermal-induced stress causing a significant crack; and (b) wall delamination

For a reactor safestore, the NDT challenge/opportunity is to penetrate through the large concrete sections (or masonry) to determine long-term integrity that can be justified to the nuclear regulator, the Office for Nuclear Regulation (ONR).

Inaccessibility of buried structures, for example dock walls, cooling ponds and reactor basements, is a particular challenge. There is concern that water ingress in these areas could affect the long-term integrity of the structures by causing localised wall delamination or whether water egress will contaminate ground water. NDT should be employed to inspect water bars.

Current NDT techniques used in civil engineering structures are either simple, slow or costly, with limitations in imaging. Techniques that are used include:

- GPR;
- Cover meters;
- Rebound hammers;
- Ultrasonic pulse-echo (this requires a detailed knowledge of concrete) – limited use;
- Radiographic techniques (gamma and X-rays) to define voids and rebar layout – seldom used; and
- Subsurface radar – limitations to simple planar surfaces.

Many of these techniques are difficult to deploy in a nuclear environment (*ie* electromagnetic interference (EMI) or electromagnetic pulse (EMP), radar or X-ray affecting essential electrical control systems). There is a need for innovative NDT in the nuclear industry (and civil/structural engineering in general) to predict the long-term ageing and the structural condition of assets. In particular, new techniques are required for the inspection of large areas of concrete and in inaccessible areas. Evidence is required of the structural condition and asset integrity to support safety cases and review by regulators (ONR or the Defence Nuclear Safety Regulator (DNSR)).

Regulators need confidence in the condition of nuclear assets; there is an opportunity to develop new NDT technologies and techniques, including remote deployment, to improve confidence in structural assessments.

6. Session 5: Potential future NDT and SHM requirements – transfer from other sectors

Session 5 considered the application of NDT/CM/SHM in other industrial sectors and examined whether there are processes, technologies, operator certification and other practices that could be transferred into the civil engineering sector to provide a benefit.

6.1 Overview of BINDT and RCNDE and their roles in developing NDT techniques

Colin Brett, BINDT and RCNDE

Colin Brett provided an overview of the British Institute of NDT and the UK Research Centre in NDE, including an explanation that this workshop was part of an ongoing series intended to capture the requirements for NDT from different areas and sectors across industry.

BINDT is a professional engineering institute that serves the needs of all people engaged in NDT/CM/SHM, whether as practitioners, researchers, suppliers, trainers or managers. It organises an annual conference and other events, produces a journal (*Insight: Non-Destructive Testing and Condition Monitoring*) and other publications, and runs Working Groups on specific technologies, standards, training and certification, etc, for the overall improvement of the inspection industry. RCNDE is an industrial/academic research consortium that manages and undertakes research projects in areas of importance as deemed by its industrial members. Inevitably, BINDT and RCNDE often work together to advance the fields of NDT/CM/SHM.

It was explained how BINDT, RCNDE and industry work together to create an inspection methodology/technique/system that can be used in the field to provide meaningful information on the condition of an asset or component.

The lifecycle of an NDT technology can be tracked using Technology Readiness Levels (TRLs), which quantify the level of development of a project from basic R&D, then through prototype development, technology transfer routes, validation of techniques, personnel training and qualifications and finally full implementation in the field (see Table 5).

Table 5. Technology Readiness Levels (developed by NASA in 1974 to define the technological status of a project)[10]

TRL	Phase	UK government description
9	Phase 4: Launch	Actual technology qualified through successful mission operations
8	Phase 3: Commercial system development and validation	Actual technology completed and qualified through test and demonstration
7		Technology prototype demonstration in an operational environment
6	Phase 2: Prototype development	Technology model or prototype demonstration in a relevant environment
5		Technology basic validation in a relevant environment
4	Phase 1: Basic R&D	Technology basic validation in a laboratory environment
3		Analytical and experimental critical function and/or characteristic proof-of-concept
2		Technology concept and/or application formulated
1		Basic principles observed and reported

- **Phase 1 – Basic R&D** is completed by RCNDE universities (including students in the Future Innovation for NDE (FIND) Centre of Doctoral Training) with a mixture of industry and government funding. Requirements workshops are held periodically to support gathering the industrial needs for NDE. The RCNDE industrial vision[11], revised every five years, provides strategic guidance based on industrial corporate needs.
- **Phase 2 – Prototype development** enables the validity and limitations of the technology to be understood. RCNDE runs workshops for industry to provide insights on technology readiness, identify any gaps and consider the risks involved. The annual RCNDE Technology Transfer event provides further information on technology transfer projects and is open to RCNDE Industry and Associate members. The first steps to move technologies into the field are often taken by industry and/or the Engineering Doctoral (EngD) students working in industry.
- **Phase 3 – Commercial system development and validation:** Within RCNDE, it is possible that a university may set up a spin-out company to take forward the further development required for full commercialisation. Alternatively, an Associate member might be better placed to develop and exploit a technology. The development of inspection procedures is typically completed by industry to adapt the technology to its specific needs. Together, BINDT, RCNDE and industry support the development of standards, development of training courses, test samples and examination/certification question sets. If required, BINDT is able to set up certification for personnel through its Personnel Certification in NDT (PCN) Scheme, which it administers.
- **Phase 4 – Launch:** In industry, the technology/methodology is routinely used by trained and accredited operators. Equipment and software are available to purchase and services are offered for the application or hire. Improvements are identified for the next generation and fed back to lower TRLs and research continues within RCNDE universities on this and on the next new technologies (replacements).

The routes to technology exploitation were highlighted and include publishing, consultancy, open-access software (if appropriate), licensing, spin-out companies, transition to industry via an EngD student, etc (see Table 6).

Table 6. Routes to technology exploitation

Exploitation route	Description
Publish	Publish only. No further consultancy, procedure, working with members, etc
Consultancy	Publish and consultancy
Members	Publish and make available to RCNDE members via consultancy, EngDs, etc
Open access software	Open access software, including open source
Spin-out	Spin-out company set up, with or without patent
Licence	Single-supplier licence, with or without patent
Procedure	Publication of a procedure or standard, of direct application
EngD	Transitioned through an EngD student
Algorithm Deployment Support Service	Multi-supplier by transitioning software engineering documents using the MTC's ADSS

6.2 Development of geoelectrical imaging for the remote condition monitoring of engineered structures

Jon Chambers, British Geological Survey

Jon Chambers is Head of Shallow Geohazards and Earth Observation at the British Geological Survey (BGS).

BGS's innovation goal is to make novel geophysical subsurface imaging technology relevant, useful and available to the engineering and environmental communities.

Geophysical measurement and monitoring are based on electrical resistivity tomography (ERT), where electrodes inject current into the ground and measure the resulting voltage, from which resistivity can be determined. Different materials, for example sand, soil, concrete, etc, will have a differing resistivity. By surveying an area, an image can be constructed (see Figure 21).

A system called PRIME has been developed to enable ERT monitoring of areas and has been evaluated in pilot studies between 2015 and 2022 (see Figure 22).

Case study for ERT monitoring using the PRIME system: seepage monitoring of an old dam

Seepage, which was particularly prevalent at high water levels, was noticed from a reservoir dam constructed in the 1700s. There was little information regarding the design, structure and core of the dam. However, the PRIME system was able to provide resistivity measurements to help locate the leak sources and seepage pathways through the dam and provide information on the condition of the dam (see Figure 23).

Novel ground imaging technology has been proven for remote condition monitoring in geotechnical, hydrogeological and geohazard applications. Wider applications could include bridge, tunnel, retaining wall and culvert structures, but additional pilot studies would be required.

Innovations in measurement systems and imaging software have enabled the shift from one-off surveys to the installation of *in-situ* monitoring systems delivering imaging data from remote sites in near real time.

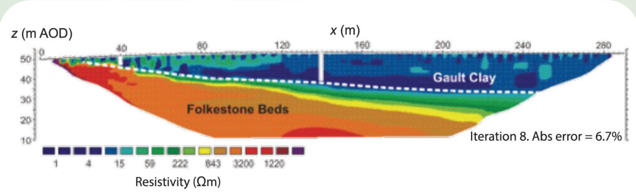


Figure 21. ERT image from survey of Folkestone Beds

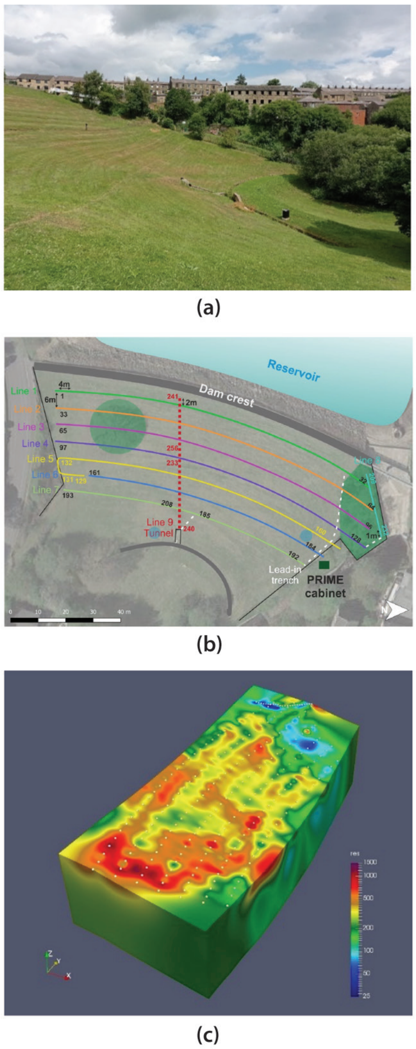


Figure 23. Seepage monitoring in a dam using ERT: (a) access to the dam via a grassy bank; (b) ERT monitoring array; and (c) ERT imagery showing notch in blue

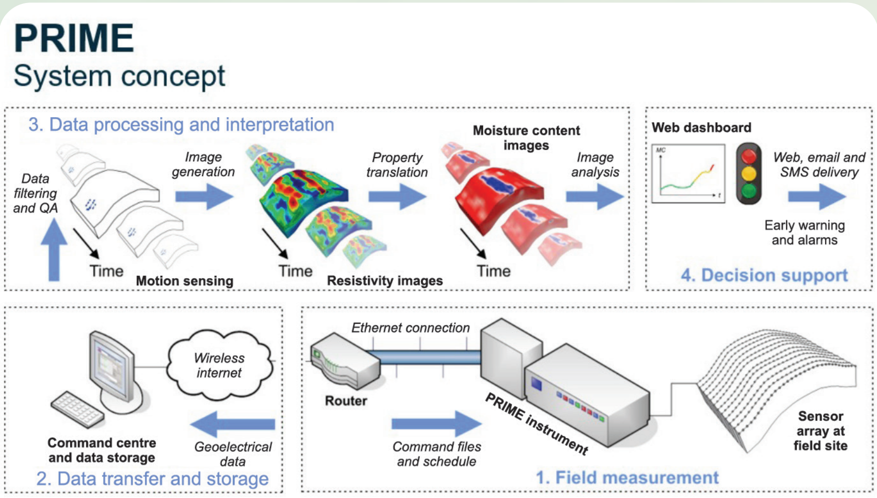


Figure 22. The PRIME system for ERT monitoring of structures

6.3 Capacitive (non-contact) resistivity imaging: technology transfer from applied geophysics to NDT

Geoelectrical imaging is an applied geophysical methodology that is increasingly being used in a civil engineering context to characterise and monitor infrastructure assets. It is effectively NDT applied to the subsurface and enables the mapping of geological (or man-made) structures and the detection of anomalies. Technology transfer has occurred from applied geophysics to non-geoscience sectors.

In ERT, imaging of electrical properties is based on galvanic contact; however, this often limits its use on engineered surfaces such as concrete, tarmac, polymers, fibre-based materials and composites. Dynamic measurements made with moving arrays are often noisy.

Capacitively coupled resistivity imaging (CRI) is a novel technology that extends the range of applications of ERT to more environments and offers new opportunities as an NDT technique that can be used on engineered materials.

The fundamentals of CRI were explained, including that the technique uses low-frequency electromagnetic measurements under quasi-electrostatic conditions. It uses non-contact plate-wire sensors or line antennas instead of galvanically coupled metal spikes. CRI is typically able to penetrate within the top ~5 m of a surface[12].

The technology has been developed at BGS from a metre-scale sensor array that can be towed to a hand-held device at the cm-scale. An example of the application of the technology on a trial road at the Transport Research Laboratory was provided (see Figure 24).

The technology has also been applied to:

- Shallow geohazards, such as detecting concealed shallow mine workings at a Roman mine in Derbyshire;
- Laboratory study of rock samples from the Grimsel Test Site in the Swiss Alps. This study was useful for determining whether sites are suitable for the disposal of radioactive waste;
- Detection of concealed structures and buried objects, such as improvised explosive devices (IEDs) or their components, arms caches, etc; and
- NDT of composites using a smaller sensor array and new sensor electronics (see Figure 25).

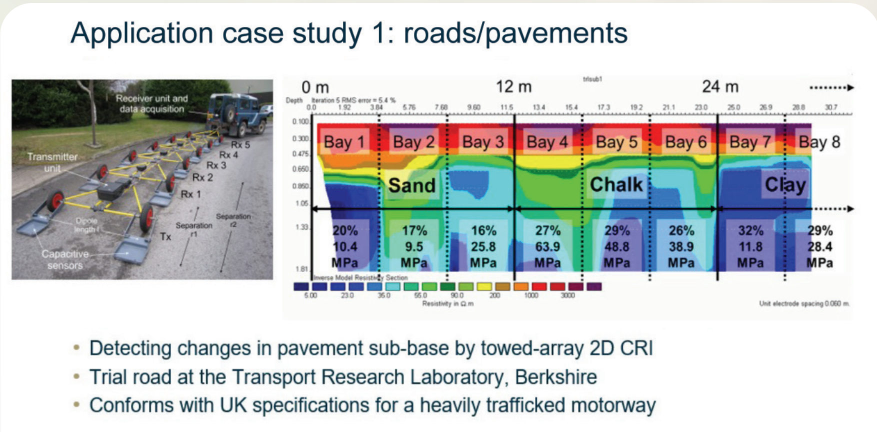


Figure 24. Non-invasive characterisation of roads and pavements at the Transport Research Laboratory

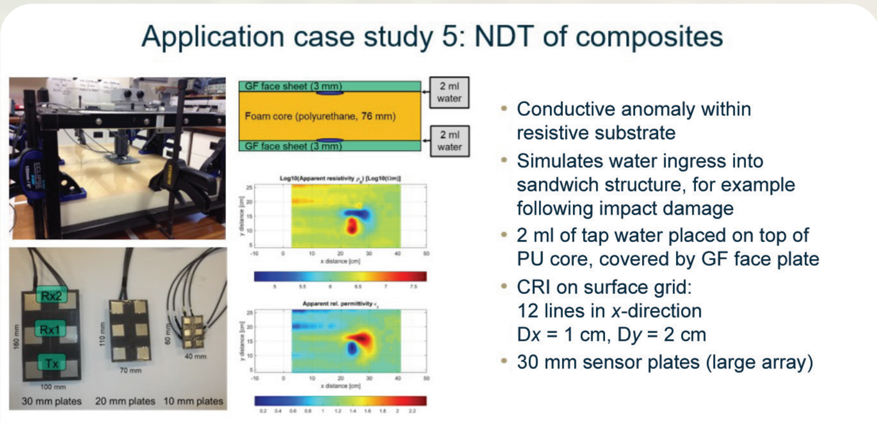


Figure 25. Use of CRI for the assessment of composites

CRI complements ERT and enables dynamic measurements with high spatial resolution. There is a new opportunity for NDT/NDE and technology transfer from applied geoscience to new market sectors.

6.4 Muon tomography (cosmic rays)

Jaap Velthuis, School of Physics, University of Bristol

Muons are similar to electrons but are about 200 times heavier and are produced when cosmic rays interact with particles in the atmosphere. There is a constant flux of muons bathing the Earth's surface, where they can be used for imaging. They occur naturally at rates of about 100 Hz/m^2, are highly penetrating and have been measured at depths the equivalent of 10 km of water. They provide the opportunity to study structures from a safe distance by taking measurements before and after penetration through a structure, but they do not offer a quick inspection method. They can provide information about materials including local density, the presence and locations of air bubbles and rebars in concrete, thickness measurements of embedded objects and information on the corrosion of embedded iron, as well as the state of material under insulation.

Muon tomography relies on a direction change, which must be measured for the incoming and outgoing track. It is sensitive to the atomic number (Z) of an element; for example, in steel, muons will only undergo a small deflection compared to that seen in uranium.

Muon radiography, measuring the absorption along the line of the muon track with two detector stations, will be a better technique for large objects.

An explanation of muon scattering tomography, and the novel data reconstruction method, was provided.

Examples of muon inspections:

- **Civil inspection** – Muons are able to detect density changes in concrete and detect air pockets (see Figure 26).
- **Corrosion under insulation** – Muons have detected air and rust holes in an insulated 50 cm-diameter, 1.8 cm-thick steel pipe after only six hours' exposure (see Figure 27).
- **Air bubbles in concrete** – In nuclear waste drums there is an interest in any bubbles in the concrete and bitumen. Muons can detect and locate single and groups of bubbles. This can be useful for inspection of concrete walls/floors with potential bubbles.
- **Rebar detection and location** – Muons have been successful in the detection and location of 6 mm rebars in 340 mm of concrete (see Figure 28).

Muon tomography is a novel technique for civil inspections. It provides information on objects embedded in concrete, including bubbles, and it can determine the density of concrete, detect corrosion under insulation and detect and locate the presence of rebars, as well as being used for many other applications. Muons can penetrate through kilometres of rock, and therefore through entire buildings, and can be used to monitor from a safe distance. The measurements do not interfere with other activities.

Muon tomography has many applications and is a very promising tool for NDT.

Figure 26. Example of an air pocket that can be detected using muons

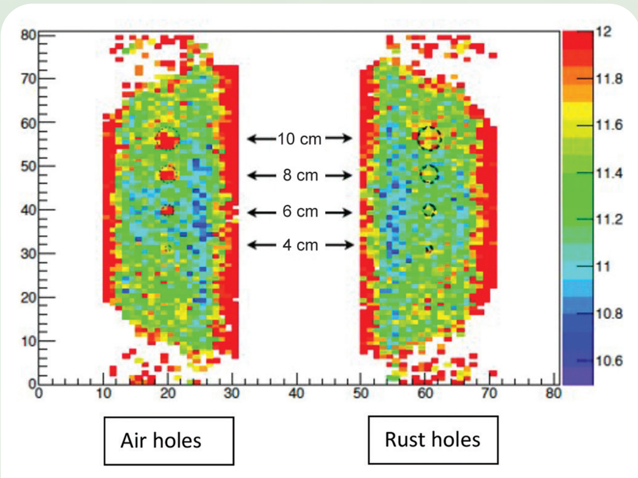


Figure 27. Images of air and rust holes detected in a 50 cm-diameter, 1.8 cm-thick steel pipe with muon technology (the holes were 4 cm, 6 cm, 8 cm and 10 cm in diameter)

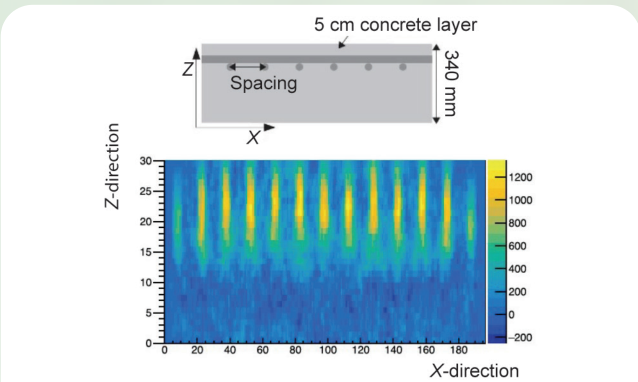


Figure 28. Detection and location of 6 mm rebars in 340 mm of concrete

6.5 The potential use of terahertz NDT on civil structures

Mira Naftaly, National Physical Laboratory

The terahertz (THz) range spans 100 GHz to 10 THz and sits between the regions considered to be electronics (microwaves) and photonics (infrared) in the spectrum.

The application of THz NDT is non-contact, non-ionising, non-destructive and sensitive to variations in complex permittivity, structural and compositional inhomogeneities.

There are numerous applications of THz across a range of non-conductive materials. These materials include plastics, composites, foams, paper, paints, adhesives, glass, ceramics, cement and concrete. It can be used to determine coating thickness and uniformity, detect any delamination or adhesion layers, detect corrosion under coatings or moisture between a coating and substrate. It is limited to only thin structures between 5 mm to 50 mm.

Table 7 provides examples of the penetration depth for THz transmission through a variety of materials at two different frequencies. Note that the thickness given allows 10% transmission of the THz and is the maximum thickness that allows measurements to be taken.

Table 7. Transmission of THz through materials; note that the thickness provided is the maximum to allow for measurements to be made

Material	Penetration at 0.1 THz	Penetration at 0.5 THz
Wood	10-30 mm	2-6 mm
Brick/plaster/ cement/concrete	10-20 mm	1-4 mm
Glass/fibreglass	10-30 mm	1-5 mm
Plastics (PVC/PA/acrylic)	20-60 mm	3-12 mm
Plastics (PE/PC/PTFE)	300-600 mm	100-300 mm

There is coarser spatial resolution when using lower frequencies, for example 1 mm at 1 THz and 10 mm at 0.1 THz.

Terahertz time-domain spectroscopy (THz TDS) is the usual methodology employed and measures the amplitude, phase and time-of-flight. TDS performance covers a bandwidth of 5-6 THz and has a one-shot spectral acquisition and a frequency resolution of 1-10 GHz.

Applications in the civil sector include corrosion under insulation, coating inspection (see Figure 29)[13], moisture ingress and pipe structures including coaxial cables. The use of terahertz is a promising NDT technique for the civil industry.

An audience member asked if THz measurements could be used to inspect the waterproofing layer on a bridge deck under several inches of tarmac. It was noted that any rebars present might cause an issue, but if the rebars could be detected using GPR the resistivity results could potentially be separated from the overall resistivity response. Further work would need to be performed to investigate this.

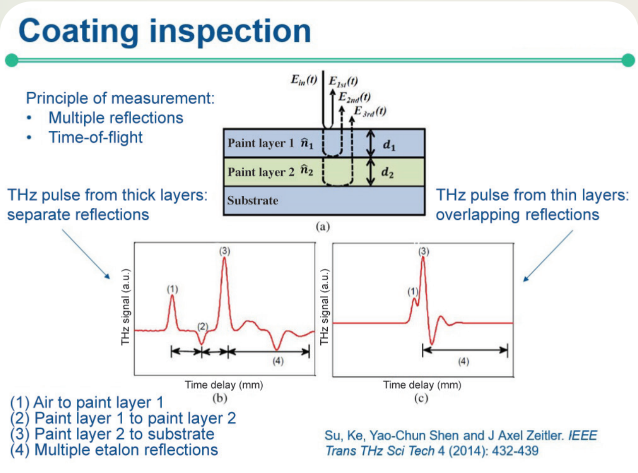


Figure 29. Coating inspection using terahertz radiation

7. Session 6: Breakout session

A second breakout session was held at the end of Day 2 in which all the participants were again invited to contribute to five separate topics before reconvening to review all the responses.

The five topics were to consider:

1. Non-destructive testing/condition monitoring/structural health monitoring experiences from the field;
2. Benefits of future non-destructive testing/condition monitoring/structural health monitoring improvements;
3. Highest priority future requirements;
4. Potential contributions from other sectors; and
5. Civil-specific skills, training and certification requirements.

The summary of responses is given in Table 8.

Table 8. Summary of responses to the breakout session on Day 2

Topic 1: NDT, CM and SHM experiences from the field

- There would be a benefit in the sharing of near misses/failures because the civil industry is usually reactive to failures. It would be better to look at trends, deterioration and near misses rather than wait for a major structural failure. This already happens in other industries, for example oil & gas, nuclear, power generation, aerospace, etc.
- Look at the success of guidance documentation from other industries – how to mimic successful deployment of NDT/CM/SHM in other industries; how to communicate best practice.
- Sharing of knowledge about successful locations, orientations and configurations of NDT/CM/SHM sensors and how results can be optimised.
- Similarly, the sharing of unsuccessful uses of NDT/CM/SHM; understanding why it did not work and avoiding repetition of mistakes.
- From the client's perspective, one of the key issues is defining the reliability/accuracy of NDT/CM/SHM methods, *ie* something quantifiable and usable. There is often not much hard information in SHM, which can be a bit vague. More open discussion about what type of reliability/accuracy of different methods would be necessary.
- Different deterioration defects and flaws arise when new materials are used, for example high-strength steel. They will ultimately need a corresponding inspection tool or technique suited to them.
- There needs to be some job-/task-specific inspection procedures for common problems.
- There is a need to have clear problem statements; setting of expectations from the client's side.
- There needs to be greater consideration of the use of recycled materials and how that would affect NDT if we started embedding recycled materials into other materials.
- Promotion of the value of using NDT/SHM for design. Avoid the lowest minimum being the standard.
- The effect of human factors on the success of inspections needs more exploration.

Topic 2: Benefits of future NDT, CM and SHM improvements

- The main benefit of NDT, CM and SHM is to provide information that will help to inform better decisions.
- It will help to reduce/eliminate subsequent intrusive work that could be damaging to a structure.
- A reduced need to interrupt asset operation.
- Prolong the life of assets and facilitate the reuse of structures. Better sustainability and promotion of the circular economy.
- Smarter deployment of NDT, CM and SHM will improve objectivity and confidence in results. As confidence in results improves, there is a smaller need to do testing. In the civil sector there will always be some intrusive testing for validation. However, this could be minimised by using new approaches such as multi-sensor techniques and data fusion techniques to obtain complementary assessments of the condition.
- Reliability in speed and the ability to start automating and having robotic applications. Deliver and access potential benefits around SHM – once we can start putting better SHM on drones and using it reliably we could overcome some of the limitations and application constraints.
- Gathering data to support more risk-based approaches to evaluation, to support more probabilistic approaches to design and reliability-based approaches. This will lead to the ability to design structures more efficiently, keeping them in service for longer by understanding them better.
- Improved transparency and understanding of the data, data interpretation, algorithms, visualisation, etc. This will allow the non-specialist to interact and understand the data better.
- Opening the door to the use of new and innovative materials. NDT could help in giving civil engineers more confidence in using new materials or materials perceived as risky. This would realise the benefits that the use of those materials could bring.
- Opportunity to improve quality during construction, ideally without adding costs so the contractors do not push against it. This would improve confidence and reduce insurance premiums, etc. Better information will lead to a virtuous circle that will bring benefits to the civil sector and society in general.

Table 8. Summary of responses to the breakout session on Day 2 *continued*

Topic 3: Highest priority future requirements
• Standardisation of the methods that comes with maturity and greater use in the field to know what the standards need to be; pulling experience from the field to formulate codes and standards (with an application focus). • Human factors: the results you get can depend on the person doing the test and the environment. What can we learn from the existing literature (avoiding the cost and time of repeating studies)? • Related to human factors: some problems can be avoided by auto-screening data; use machine learning to detect anomalies and refer those to a human for assessing what to do with them. The human then deals with the exceptions and is not overwhelmed by a multitude of innocuous data. • Make smarter structures from Day 1, rather than retrofitting or reacting to problems. Try to install sensors from the start to gather data as you go along. • There is a need for a deeper/broader training of civil engineering undergraduates and new-starter staff in the range of NDT, CM and SHM methods. This could be at an 'appreciation' level and not necessarily specialist.
Topic 4: Potential contributions from other sectors
Many NDT, CM and SHM methods are in regular use in other industry sectors and the users often have clear views on areas of weakness and shortfalls in capabilities. This, in turn, leads to development programmes, either within a sector or cross-sector, that aim to improve those capabilities. The results will, in time, become available more generally, but there are several methods that would benefit from a more active engagement from the civil engineering sector in order to produce systems that are tailored to its needs. Examples include: • There has been some recent work in improving the resolution of ground-penetrating radar images by combining responses from different antennae to create a synthetic, focused image[14,15]. This will produce images that show internal features more clearly, requiring less specialist interpretation. • Highly sensitive gravitometers based on quantum interference effects can help to infer what is underground. These devices are starting to move out of the laboratory and have been trialled on identifying variations in bedrock and groundwater, as well as other natural and artificial variations in the ground such as landfill and mine workings[16]. • Digital image correlation (DIC) methods can detect strains in the surfaces of large structures from a remote location without the need for surface preparation[17]. Advanced processing methods can also identify vibrational modes. • The creation of high-resolution point cloud images can be used similarly to identify trends. • Installed fibre-optic cables (fibre Bragg gratings) could be used to measure strains, temperature, corrosion products, etc, in a structure. • Developments are underway to use NDT methods to measure material properties, for example tensile strength of steel, degree of tempering, etc. Related methods could potentially be developed to measure the properties of concrete, such as the degree of cure.
Topic 5: Civil-specific skills, training and certification requirements
• At the moment, there is no ISO 9712-compliant NDT and CM training/qualification certification scheme that is specific to civil engineering. Only niche schemes exist, such as the BICS, where the focus is on visual inspection for highways. • There is a need for CM- and SHM-specific training and accreditation. • UKAS accreditation of a certification scheme and defined governance processes must be in place. • NDT is covered in mechanical engineering at some universities, but not all. There is maybe space for NDT/CM/SHM to be taught in civil engineering courses. This would need PEI accreditation of the courses and the Engineering Council might have additional requirements. • There is a need for some general appreciation courses on NDT, CM and SHM for all parts of civil engineering so that there can be greater engagement between designers, constructors, service providers and the client. At the moment it is perceived to be a black box. • Guidance documentation on when to use in-house *versus* certified externally/third-party inspection is needed. • Mentoring and coaching are important for newcomers to the field.

8. Session 7: Discussion of key requirements

The final session drew together the key issues that had been raised over the two days of the workshop. A panel was invited to provide top priorities for improvements. The panel consisted of:

- Jon Watson (Mistras)
- Leo McKibbins (Mott MacDonald)
- Steve Dennis (Office of Rail and Road)
- Dave Cousins (James Fisher Strainstall)
- Andy Moore (CIRIA)
- Tim Abbott (Mott MacDonald).

The panel and audience then discussed the steps that would be required to bring about positive changes to improve how inspections are managed and delivered within the civil sector. All the items had been raised several times during the course of the workshop, often by organisations having different perspectives, but this session helped to draw them together into an overall summary.

Expanded information on some of the topics discussed, particularly on practices and processes relating to NDT/CM/SHM that might be less familiar to the reader, can be found in Appendix 2.

Reliability of inspections

The majority of the panel members gave 'reliability' as the topmost priority, broadly meaning that there must be consistency and accuracy in the inspection data that is provided to the client.

The need for reliability of NDT/CM/SHM is not unique to the civil sector but is common throughout all industry. Systems and processes have evolved within other sectors, for example nuclear, power generation, aerospace and oil & gas, to help ensure that NDT/CM/SHM services can be delivered in a consistent and meaningful way, so that decisions about the future operation and safety of a particular asset can be made with confidence. The systems are not perfect and are always subject to change as new and better technologies emerge, but they factor into the following components:

- Procedures;
- Equipment and sensors; and
- Operator competence.

Information on how these aspects can be optimised to improve reliability can be found in Appendix 2.

Validation of inspection techniques

One panel member mentioned improving the POD of a defect as the highest priority item. This, of course, is closely linked to the items discussed above.

POD is a description of the detectability of a particular size of defect and typically ranges from zero for very small defects to close to unity for large defects[18]. Different inspection methods and different sensors will all produce their own POD curves and the science of inspection is to select the optimum combination of method and sensitivity for a given inspection task having defined objectives. Note that it is assumed that the inspection is performed by a perfectly competent operator, so those variables are not included in the analysis.

The point raised by the panel member was that POD is poorly understood in civil engineering, even for commonly applied inspection techniques.

Again, this is not solely a concern of civil engineering but is common throughout industry. BINDT operates a Technique Qualification and Validation User Group that originated in the aerospace sector but which is now cross-sector. It is proposed that a representative from civil engineering should be invited to sit on this user group to raise specific concerns and for more general networking benefits.

Management of inspections

A topic that was raised several times during the course of the workshop and again by the panel was the issue of the interpretation of inspection reports that are received by the client from the inspection service provider. Another panel member stated that the priority was for 'information' to be provided rather than 'data' as, very often, the client does not have the expertise to process and interpret the raw data into a defined course of action by themselves.

Often it is left to the procurer of NDT/CM/SHM services to interpret the results in terms of the operational risks and the actions that are needed in response to the inspection; the classic 'run, repair or replace' decision-making process. If the procurer is not an expert in the inspection method and how it has been deployed, how are they to make sense of the waveforms and plots that are usually provided in an inspection report? Conversely, if the inspector is unaware of the stresses within a structure or has no idea of the intended duty cycle, how can they know the size of the defects that can be tolerated? There is a clear gap in understanding here.

Many companies in other sectors employ dedicated staff with relevant expertise to address these issues, as expanded on in Appendix 2, but, as a partial solution, it was suggested by a member of the audience that some 'NDT appreciation' courses could be provided that would give an overview of the main methods and capabilities, without going into the minute details that would be needed by someone aiming to become a practitioner. This would allow someone who was not an inspection specialist to at least help with writing contract specifications and to ask some sensible questions of any service provider. Such courses have existed in the past, provided by some NDT training schools, and still exist within specific companies to educate new starters and provide a wider engineering context to their staff. Consideration could be given to the development of a focused appreciation course for civil engineering personnel.

Sharing sector experiences

Another panel member gave the sharing of experiences in the civil engineering sector as the highest priority. The workshop highlighted that there were several common problems and that solutions to some of them might already exist. If the sector maintained a database of inspection issues that need improvement, or capabilities that need to be initiated, then it would provide a reference point from which decisions could be made on which items to take forward for possible solutions. Whilst the sector is fragmented it is unlikely that any single company will create enough momentum to solve an issue, but collaboratively it might be possible.

Andy Moores of CIRIA offered to set up a system to capture specific problems. As an initial example, it was suggested that the capability to form better resolved images of rebars in concrete would be a good case to include, as it is a concern of many organisations.

Greater engagement with insurance business

It is clear that modern inspection methods can bring benefits at all stages of a project. The elimination, or at least partial reduction, of flaws that are introduced during the construction phase could significantly reduce the probability of a component failure during operation and lead to a reduction in the cost of any corrective activities that might be necessary after that failure. Similarly, the introduction of technologies to monitor structures during operation can reduce the probability of an unexpected failure and also allow maintenance to be scheduled based on the actual risk at the time of inspection and not after a prescribed time period when, perhaps, an inspection is unnecessary.

Both of these benefits will reduce the operation and maintenance costs for the owner, increase the safety of the asset and lower the risk of harm to personnel and the environment, but will clearly involve extra costs at an earlier stage in order to realise. The degree to which any improved asset management practices are undertaken will clearly be influenced by a cost/benefit analysis and part of this should include the cost of insurance. It is therefore recommended that the civil engineering community and the insurance business should seek a greater mutual understanding in order to realise the benefits.

9. The way forward

In summary, the workshop has identified the following actions to foster closer working relationships between the civil engineering and non-destructive testing/condition monitoring/structural health monitoring communities:

1. BINDT to invite representative(s) from the civil engineering community to form a civil engineering sub-group, reporting to the BINDT Technical Committee. This will be an opportunity to discuss any NDT/CM/SHM matters relating to civil engineering (methods, certification, research needs, etc) as well as to help make contact with inspection personnel from other industrial sectors.
2. BINDT to invite a representative from the civil engineering community to sit on the cross-sector Technique Qualification and Validation User Group. This will provide greater experience about how inspection reliability can be measured and improved.
3. CIRIA to launch a service to collect information about common inspection problems and challenges. This will help to prioritise topics that could benefit from a collaborative response to developing solutions.
4. RCNDE/BINDT to increase their exposure at civil engineering conferences by making overview presentations and/or having a stand at accompanying exhibitions. This will help to reinforce links and publicise channels for tackling inspection issues.

Acknowledgements

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Appendix 1: Delegate list

Tim Abbott	Mott MacDonald
Michael Aerts	Sercal NDT Equipment Ltd
Dylan Badwal	Stork
Miguel Bravo-Haro	Cambridge Centre for Smart Infrastructure
Colin Brett	RCNDE
Caroline Bull	RCNDE
Paul Cairns	Mistras Group (Exhibitor)
David Castlo	National Rail
Fred Cegla	Imperial College London
Jon Chambers	British Geological Survey
Tom Cosgrove	Sandberg LLP
Dave Cousins	James Fisher Strainstall
Adam Davey	Marsh
Martin Davison	Concrete Preservation Technologies Ltd (Exhibitor)
Nigel Davison	Concrete Preservation Technologies Ltd (Exhibitor)
Julie Dell	Sandberg LLP
Steve Dennis	ORR
John Drewett	Concrete Repairs Ltd
Graham Edwards	TWI
Joshua Elliott	The Manufacturing Technology Centre
Cailean Forrester	Inspectahire Ltd (Exhibitor)
David Gilbert	BINDT (CEO)
Yashar Javadi	University of Strathclyde
Nicko Kassotakis	University of Exeter/Imetrum
Oliver Kuras	British Geological Survey
Mike Laws	The Manufacturing Technology Centre
Ellis Lester	University of the West of England
Peter Loftus	RCNDE
Hazel McDonald	Transport Scotland
Bill McKeown	The Concrete & Corrosion Consultancy Practice Ltd (Exhibitor)
Leo McKibbins	Mott MacDonald
John Moody	BINDT
Andy Moores	CIRIA (Exhibitor)
Mira Naftaly	National Physical Laboratory
Michael Nugent	The Concrete & Corrosion Consultancy Practice Ltd (Exhibitor)
Phil Pearson	Consultant
Gareth Pierce	University of Strathclyde
Nigel Pierce	CRL Surveys Ltd
Will Reddaway	East West Rail
Paul Rogger	JR Technology (Exhibitor)
Neil Sandberg	Sandberg LLP
Robert Smith	RCNDE
Simon Tewolde	Bachmann Monitoring GmbH
Michael Thorne	VINCI Technology Centre UK Limited
Andrew Threlfall	Costain
Adrienn Tomor	Brunel University
Shirley Underwood	Screening Eagle
Jaap Velthuis	University of Bristol
Sam Wadeson	JME
James Watson	Jacobs Engineering
Jon Watson	Mistras Group (Exhibitor)
Paul Wilcox	University of Bristol
Jack Young	CIRIA (Exhibitor)
Jie Zhang	University of Bristol

Appendix 2: Expanded information supporting the final panel session

The final session of the workshop, Session 7, was a panel session that summarised the main findings from the workshop. This appendix contains supporting information relating to the topics that were discussed and is intended to explain some of the processes and practices that are used by practitioners in NDT/CM/SHM and which might be less familiar to the civil engineering community.

Reliability of inspections

The top priority identified by the panel members was 'reliability', broadly meaning that there must be consistency and accuracy in the inspection data that is provided to the client.

The need for reliability of NDT/CM/SHM is not unique to the civil sector but is common throughout all industry. Systems and processes have evolved within other sectors, for example nuclear, power generation, aerospace and oil & gas, to help ensure that NDT/CM/SHM services can be delivered in a consistent and meaningful way, so that decisions about the future operation and safety of the particular asset can be made with confidence. The systems are not perfect and are always subject to change as new and better technologies emerge, but they factor into the following components:

- Procedures;
- Equipment and sensors; and
- Operator competence.

Taking each of these factors in turn:

Procedures

A procedure is a document that describes in sufficient detail the steps needed to perform an inspection, specifies the equipment needed and describes the level of operator competence required. They can range from a single page for a routine, well-established task to many pages for a more complex situation. The text will define what its objective is in terms of defects sought, explain how to position and scan sensors, how to select which data to measure or capture and how to process that data into information that describes the defect. In principle, data collected at two different times will be directly comparable if the same procedure has been used.

It should be noted that a procedure provided by one service provider is not necessarily the same as a procedure provided by another. It is not uncommon for service providers to have generic procedures that can be used for multiple clients on multiple tasks, so, unless a clear specification is provided by the client for the particular inspection task, it is possible to produce two sets of data that have little correlation with each other. It therefore follows that, in order to achieve meaningful and comparable results, the procedure must be specific to a particular inspection task, and to be specific, the inspection service provider must know the objectives of the inspection in terms of the defects that are sought (note: specific procedures are often called 'techniques'). This demands a greater level of involvement in the specification stage of an inspection, rather than as an activity that is brought in as an addition.

Equipment and sensors

It is clear that all equipment needs to be in working order and that the performance characteristics should be traceable to national or international standards. There is also a need to ensure that it is calibrated correctly before a particular task and that it is set to the correct sensitivity. This should be checked periodically throughout an inspection to check for any drift that might have occurred, perhaps because of temperature changes.

Relevant calibration samples should be available for each inspection task and they should be consistent across all service providers, again to ensure consistency. It is recognised that in civil engineering, some of these calibration samples might need to be relatively large and therefore will be difficult to transport. Nevertheless, some means of standardisation should be attempted.

For CM and SHM applications, the situation is less clear as comparisons are often made with a good baseline condition, and that could be difficult to define as the geometry and materials of construction of structures vary so much. However, any inspection report should clearly state how the equipment has been configured in order to support repeatability.

Operator competence

The third part of the reliability jigsaw is operator competence. This relates not just to the level of training achieved but also to experience of the actual inspection task. Knowledge of the properties of different materials, the types and distributions of the defects that are expected and simply the terminology for the different components all help to achieve an inspection that will be successful. For this reason, highly experienced inspectors working in aerospace tend not to work on nuclear applications, and *vice versa*, despite holding equivalent levels of certification.

Certification can either be second-party, where the client defines the various levels of achievement attained and administers the training and examinations, or third-party, where an independent body manages the whole process. In the UK, the Personnel Certification Scheme in NDT (PCN) that is managed by BINDT[19], and the CSWIP scheme that is managed by TWI[20], are examples of third-party accreditation schemes that are in widespread use. Both these schemes satisfy the qualification and certification requirements of ISO 9712[21].

There are typically three levels of competence that an individual can achieve: Level 1 tends to be for routine tasks that are supervised and is often an entry level; Level 2 is a higher level where the operator can work unsupervised – this is often the most appropriate level for a field inspector; and Level 3 is for a more experienced operator who is conversant with multiple inspection methods and who has the authority to amend and authorise procedures. An individual who has been certified in a range of methods might hold different levels for each method. Note that if a company does not employ an individual holding a Level 3 in a particular method, it is possible to engage an external body to fulfil that role.

Importantly, accreditation schemes such as PCN and CSWIP are led by industry, so the range of training and examinations is constantly being updated to reflect changing requirements. For example, recently a range of courses has been set up to accommodate the growing need to inspect composite materials as used in aerospace. BINDT operates a number of working groups and committees that allow companies having a common interest to come together to discuss their needs in detail and to progress those ideas through to a deliverable. For example, there is an Aerospace sub-committee that reports to the Technical Committee and it would be simple to set up a similar sub-committee that is devoted to civil engineering to pursue NDT/CM/SHM matters.

Related to operator competence is the topic of human factors that has been raised several times during the course of the workshop.

Human factors

It has been noted that even a perfectly competent operator who is completely familiar with the inspection task can still produce unreliable data. Many inspections have to be performed against a deadline, forcing the inspector to rush certain aspects or skip calibration stages, etc, and the effects of temperature, wind exposure, submersion in water, confined spaces, working at height, etc, can all lead to a deterioration in the inspector's performance. Then there is the question of how long the operator has already been working for, the time of day, the time of month and issues from their domestic life that might also be on their mind. None of this is unique to civil engineering, but all industries share these concerns and research has been underway for many years in an attempt to understand and minimise their effects. The simplest solution, of course, is always to provide a safe and conducive working environment and allow adequate time for an inspection.

Management of inspections

Often it is left to the procurer of NDT/CM/SHM services to interpret the results in terms of the operational risks and the actions that are needed in response to the inspection: the classic 'run, repair or replace' decision-making process. If the procurer is not an expert in the inspection method and how it has been deployed, how are they to make sense of the waveforms and plots that are usually provided in an inspection report? Conversely, if the inspector is unaware of the stresses within a structure or has no idea of the intended duty cycle, how can they know the size of the defects that can be tolerated? There is a clear gap in understanding here.

Many companies in other industrial sectors operate departments that contain specialist NDT/CM/SHM staff who are not only familiar with the range of inspection methods that are available, but who are also familiar with the operational requirements of the components within that sector. They often work alongside materials and structural assessment specialists who offer similar expertise in their fields. Together they can act as the interface between external service providers and the wider company. They are in a position to be able to specify the inspections that are needed, the methods to use and the defects that must be found from a position of knowledge and are able to interpret the service provider's reports in terms that the client can understand and therefore help develop future courses of action that are sensible and relevant. In addition, they can also challenge service providers by performing audit and surveillance of their work. Furthermore, these individuals will develop a strong idea of the shortfalls in the inspection capabilities that are needed to support their company and can therefore propose research projects that will develop solutions.

It is recognised that dedicated inspection departments within civil engineering companies appear to be the exception rather than the rule, but it is suggested that there would be a benefit in considering the engagement and development of such staff.

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