Asset Management Transformation Project

Post-Tensioned Non-Destructive Testing and Monitoring Techniques - Assessment of Available Methodologies

Highways England

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Contents

Purpose

As part of Highways England's Asset Management Transformation Programme, a number of workstreams are being pursued in relation to the approach to post-tensioned bridges. This document is intended to capture current best practice and potential innovative technological solutions employed for the management of these structures around the world, with a particular focus on remote monitoring and Non-Destructive Testing (NDT) techniques for post-tensioning systems.

Introduction

Prestressing technology originated in the early 1900s, with the first UK designed prestressed concrete bridges being built in the late 1940s (1). Since their inception, they have become a common technology around the world, particularly where long, slender spans are necessary, where it was important to control concrete cracking for durability or to reduce temporary works in the example of segmental post-tensioned bridges. In the UK alone, there are currently estimated to be in over 1200 post tensioned structures supporting the Strategic Road Network (SRN), a further 600 under the management of local authorities (2) with the number yet higher again when considering the rail network stock.

Despite their widespread use, they continue to provide a challenge for asset maintainers to inspect, assess and maintain, primarily due to the primary load-bearing element – post-tensioned strands which are often, but not always, within grouted ducts within the concrete volume – being inaccessible to most forms of inspection. The issue of their inaccessibility is exacerbated when coupled with poor workmanship, poor detailing for water management or inferior construction techniques and materials, which can lead the tendons exposed to deterioration even in more recently-constructed structures. Failure of individual strands can be progressive without any external warning signs and, in the worst case scenario, lead to brittle and catastrophic collapse of structures.

The concerns over long-term durability began manifesting in 1970s and 80s – particularly for segmental bridges – when investigations into post-tensioned bridges constructed as late as 1977 revealed that voids were present in the ducts of over 80% of the structures inspected (3). By 1980, a number of post tensioned decks were replaced due to concerns over the tendons, culminating in the collapse of the Ynys-y-Gwas bridge – a segmental bridge with both transverse and longitudinal post-tensioning - in 1985 (4). Despite frequent inspections, a sudden, unexpected brittle failure occurred, which was later determined to be due to localised corrosion of the tendons at the joints, accelerated by failed waterproofing and subsequent ingress of surface water and chlorides from de-icing salts (4) (3).

As a result of the collapse and the clear concerns, in 1992 a moratorium on the design and construction of all grouted post-tensioned bridges was issued in the UK, combined with an extensive and systematic review of the affected bridge stock to determine the associated risks. Two standards – BD 54/93 and BA 50/93 were issued to support these works and set out the methodology to be employed.

A subsequent study undertaken by TRL in 2001 (5), reported that of the 447 post-tensioned bridges that had been subject to intrusive investigations, the following levels of defects were identified:

- 50% had some degree of voiding within the ducts
- 36% had locations where tendons were not covered
- 13% had water or moisture in the ducts

- 10% had significant corrosion of tendons

Looking beyond the UK, the situation is similar, with recurring instances of deterioration. Collapses have occurred worldwide, including the Mandovi River bridge in Goa in 1986 (20 years old), the Malle Bridge in Belgium in 1992 (6) and most recently the Morandi Bridge in Genoa in 2018 - which although not a post-tensioned failure occurred due to concrete-encased bridge stays and so is analogous in this case. Much research has been undertaken in the US, where they similarly have many examples of deteriorated post-tensioned structures, such as the May Bay bridge in Virginia. When this structure was only 9 years old it required over £1m of repairs in 2001, displaying over 700 voids and many broken and corroded tendons, all as a result of poor workmanship during the grouting process (7).

Despite the 1992 moratorium (which has now been partially relaxed to allow both internal and external prestress with in-situ construction but only external prestress for precast segmental construction), as discussed above there still exist many post-tensioned structures in the UK built before the moratorium that present increased risk. Those built after the moratorium was lifted have benefited from improved detailing and grouting requirements, but still present the generic risk of tendon corrosion being triggered by water and contaminant ingress. Despite improved methodologies and materials those constructed world-wide will still be prone to the same issues. Effective inspection and analysis techniques are therefore still vital to ensure the ongoing safety of our stock of post-tensioned bridge structures and to allow interventions to be made early so that bridges can stay in service without emergency closures.

This paper reviews the available approaches to gather the required condition data to better manage post-tensioned bridges, both established and those in their infancy, and draws some conclusions as to their future usage. The focus is on technologies that minimise the need for human contact with the bridges and which reduce the possibility of human error.

Typical defects & causes

Ultimately, failure of a stressing system occurs if either the load within the system increases to an extent that it exceeds the limits of the undamaged strands or, more likely, when corrosion reduces the strand strength through section loss (8), whereupon failure is often brittle in nature. Many early post-tensioned bridges simply relied on infill concrete being placed around the stressed tendons to provide corrosion protection, but this has been found to offer very poor protection against water ingress. To give better protection against corrosion, post-tensioning strands are typically encased in a duct (either metallic or PVC), with the duct usually infilled with grout to prevent the ingress of moisture and/or chlorides. However, poor detailing, poor quality workmanship or inferior grouting materials can lead to a number of defects that may be present from construction:

- Voids within the ducts (most likely at high-points within the system)
- Bleed water accumulating during grout curing
- Soft grout surrounded by hard grout leading to galvanic reactions (8)
- Incorrect placement of ducting leading to low cover
- Poor detailing of bridge joints, waterproofing or anchorage cappings

Each of the above defects in isolation may not necessarily lead to deterioration of the post-tensioning system, however in combination with each other and through general degradation of the structure, they are likely to lead to deterioration. These defects can occur in any post-tensioned bridge, but pre-cast, post-tensioned segmental structures give rise to greatest concern due to the increased number of transverse joints - each forming a potential inlet point for water and chlorides (3).

Approach to Determining Condition

This review of available tools and technologies has been approached initially through consideration of the key areas of concern within a post-tensioned structure and those areas with high structural demand. The methods of degradation of said elements has informed the forms of detection reviewed and subsequent inspection and monitoring approaches.

Forms of Testing and Inspection

Determining the condition of internal post-tensioning systems is a process that is complex and often requires a mix of approaches, led by skilled and experienced engineers and specialists. In essence, this can be simplified to:

- Optical inspection techniques for surface-level indications of post-tension deterioration
- Numerical Modelling, often including Finite Element Analysis (FEA);
- Non-Destructive Testing (NDT), and;
- Destructive/Intrusive Testing.

Each approach has its own advantages and limitations, as shown in Table 1 below:

Table 1: Advantages and Disadvantages of Post-Tensioning Condition Appraisal Techniques

Approach	Advantages	Limitations
Optical Inspection	Human inspection is cheap and quick, can incorporate more advanced technologies such as AI interpretation of images/footage. Can utilise drones and high-resolution cameras for remote/difficult access locations	Often relies on human judgement for interpretation of surface-level indicators, and difficult access may prevent inspection. Drone technologies currently limited by Civil Aviation Authority restrictions on proximity to uncontrolled sites (i.e. live traffic).
Numerical Modelling	Can be done remotely, highlighting theoretically critical details and areas with high structural demand, and also predicting stresses and deflections for validation/comparison in on-site measurements and trials	Cannot be used directly to determine actual strand condition or in-service deterioration, but may sometimes be used to indirectly make such assessment e.g. by calibrating prestressing force against known bridge deflections
Non-destructive Testing (NDT)	Many systems/technologies exist for use, potentially identifying ducts, grout and strands, and associated defects without the need to physically interfere with the structure	All currently adopted systems have limitations and drawbacks, with significant levels of uncertainty in the accuracy of the results and many requiring physical access to be provided to the structure
Intrusive Testing	Provides absolute evidence of the condition of the tested element(s), giving information on in-situ environment, material strengths and state of corrosion	Requires access to the structural elements being tested, and causes physical damage to the structure (typically through sampling or boring into concrete, ducts, grout or tendons) so cannot be used indiscriminately. Will also only give information on a localised area, which could ill-inform assessment

Review of technologies

As set out in Table 1, the forms of testing and assessment can be broadly broken down into four areas, visual inspection, numerical, NDT and intrusive testing. In this review we are most concerned with forms of NDT and the less invasive forms of intrusive inspections. The forms of NDT can be further broken down into the categories shown in Table 2 for the technologies currently in use within the industry.

Table 2: Current forms of Non-Destructive Testing Methods (9)

Approach	Examples
Optical Methods	Direct visual inspection or optical solutions, including Digital Image Correlation utilising visible and infra-red light spectrums
Electromagnetic wave methods	Infrared thermography (IRT) and Impulse Radar (GPR)
Mechanical wave/vibration	Acoustic sounding, acoustic emission (AEM), impact-echo (IE), impulse response (IR), ultrasonic tomography, ultrasonic guided wave (GWT)
Penetration radiation	Radiography and X-ray diffraction
Magnetic methods	Magnetic flux leakage
Electrochemical methods	Half-cell potential, linear polarization resistance (LPR), Electro-impedance spectroscopy (EIS), electrochemical noise
Contact sensors	Direct contract measurements, such as strain gauges, displacement transducers and load cells

Within the review of the available literature, the study has included cross-industry applications. In addition to post tensioned concrete being used for bridges, it is used in the energy sector - in particular for nuclear containment buildings and structures – and also conventional buildings and waterfront structures. One such study by the US Office of Nuclear Regulatory Research highlighted that given the more mature and widespread use of PT structures within the bridge industry, the technologies used within the nuclear inspections are derived from bridge inspection methodologies, rather than visa-versa (10). It has therefore been observed that for the literature reviewed, the nuclear industry use similar and comparable technologies to those employed for bridge inspections, with the addition of a reliance on lift-off testing (for ungrouted tendons) at the anchorage plates to ensure that nuclear containment vessel tendons are demonstrating acceptable levels for the loss of prestress with time.

As discussed later in this paper, it is expected that NDT alone does not yet have the capability to provide all of the information to make informed decisions on the condition of a structure. Therefore, a number of key intrusive technologies are considered within this paper that will supplement the use of NDT. Table 3 below covers the key approaches and examples of the systems that may be employed.

Table 3: Existing Forms of Intrusive Testing

Approach	Examples
Materials Testing	Strand sampling and concrete/grout coring for carbonation testing, moisture content readings, etc
Breakout for visual inspection and testing	Water jetting to expose ducts and tendons, followed by visual inspection via boroscopes and air pressure testing
Embedded Sensors & probes	Embedded probes such as chloride sensors or half-cell potential testing and Electrically Insulated Tendon (EIT) monitoring
Physical Testing	Compressive strength assessments, concrete pull-off testing, tendon pull-off, slot-cutting

Commonly Adopted NDT Methodologies

The most common technologies are described in the following section, together with examples and commentary on where and how successfully they have been used. In each case, to aid clarity of use for the various technologies, each method is defined with a 'primary' and 'potential' usage with regards to internally post-tensioned structures (unless stated otherwise). In this case, 'primary' refers to a technology's most common and well-established usage. 'potential' usage refers to either a potential with further development of the technology or an application that has seen some success, but with limited accuracy and reliability. Conversely to potential application, significant limitations for known technologies has been highlighted in *italics* to aid usability of this document.

Note that in some cases where reliable usage has not been demonstrated, only a 'potential' use is stated.

Ground Penetrating Radar (GPR)

Principal use: Identification of prestressing tendon location

Potential use: Void Detection within internal ducts

GPR is a radar imaging technique that involves emitting electromagnetic pulses from an antenna, and receiving reflected pulses from internal reflectors within the scanned medium, which are in turn caused by changes in the materials' electrical conductivities (reinforcement, tendon ducts and voids) (11). This technique has been widely adopted for a number of purposes related to NDT of post-tensioning systems, as the system is comparatively inexpensive, quick to deploy through lightweight, compact scanners and high-speed in return of results (12) (13).

The usage and effectiveness of GPR for the inspection of post-tensioning ducts is mixed within the available literature, often due to the specifics of the structure and the material makeup being scanned. Where the ducts are non-metallic, there are examples of GPR being used to detect voids within internal ducts (14) (9) (11) *. However, factors such as high-density concrete or metallic ducts can render the system difficult to obtain reliable readings* (13)*, and generally cannot be used even in optimum situations to determine strand corrosion or depth and size of duct voids* (11).

In summary, in many cases GPR's use may be limited to identification and location of the post-tensioning ducts; However the usefulness of this system for this purpose alone should not be underestimated – many of the NDT techniques available require the precise location of the ducts to be known to be effective, and as such GPR can be a powerful tool when used in combination with others, particularly given that is it is typically unaffected by the presence of reinforcement meshes (8) (15).

Acoustic Sounding

Principal use: Void Detection (external ducts)

Potential use: Anchorage voids (internal and external ducts)

The sounding inspection technique is an extremely basic technique that involves striking of an exposed duct with an impactor or coin, hence determining the presence of voids or otherwise from the pitch of the impact response (11). This methodology boasts an extremely simple and effective process for determining the presence of voids within a duct, *but cannot be used to differentiate between voids, water infiltration and exposed grout. It is also generally unsuitable for inspection of internal ducts*, however in the cases where the duct has been exposed – or at anchorages – it may be a useful first test to employ for void detection.

Impact Echo (IE)

Principal use: Void Detection within internal ducts

Potential use: Grout deficiencies within internal ducts

Impact-echo is a well-established technique based on impact-generated stress (sonic or ultrasonic waves) waves introduced at the surface via a transducer or mechanical impact, with an array of sensors measuring the amplitude of the stress wave in time (8), (16). The technology can be used effectively for measurement of defects in concrete, including depth of cracks and air or water filled surface opening, requiring access to a structure from only one side.

For assessment of post-tensioning ducts, IE has been used to detect grout voids in tendon ducts both in laboratory settings and in the field (13) (3). IE can overcome the limitations of GPR in that it can be used on metallic ducts, however its purposes in these cases is primarily for the identification of voids – and then those nearer the surface are more easily identified, although it can be effective to depths of up to 800mm (17). However, although the equipment and approach is portable and quick to operate, signal analysis is complex, and requires an experienced operator to interpret the output (16).

The key limitation with IE is the inability to detect defects relating directly to the strands themselves. The determination of voids within the ducts can be used in combination with other datapoints – particularly if there is known ingress of chlorides and moisture into the concrete, this can inform the likelihood of tendon corrosion. Furthermore, the system is most effective when there is a precise understanding of the duct position (e.g within 13mm as described by Fisk and Armitage (2019), and as such is typically employed in conjunction with GPR.

Infra-red Thermography (IRT)

Principal use: Near-surface duct location and exposed anchorage assessment (including voids and deficient grout at the exposed face)

Potential use: Detection of voids for near-surface ducts

The use of IRT for assessment comes in two primary forms; passive (using natural heat flow) and active (with an applied heat source). In both cases, digital thermal cameras distinguish levels of thermal radiation, providing the ability to detect objects, flaws and localised anomalies (1).

It is often impractical to apply a heat source for in-situ structures, and therefore passive monitoring is adopted, with careful consideration as to the time of day when any inspection is undertaken; for greatest success the system should be used when the temperature gradient between the strands and the surrounding environment is at its greatest.

For external ducts, IRT can be used to detect voids, in addition to water defects and segregated grout (11). Although typically considered unsuitable for use in directly assessing internal ducts, there is some evidence that it has been used successfully with shallow post-tensioning ducts to detect near-surface voids (3).

Experiments have been carried out on a segmental concrete bridge in Florida, US subject for demolition in 2017, and provides interesting data as to the potential application and limitations of IRT (1), particularly when paired with comparative laboratory studies. In this study, it was found that for this in-situ condition, the technique showed the ability to indicate the locations of the ducts where they were closest to the surface (i.e. at duct deviators), however this was not as accurate as technologies such as GPR, and certainly could not indicate the condition within the ducts. Crude experimentation was made with respect to active measurement using a butane torch to heat an exposed strand at the cut face; interestingly the experiment showed uniform heating (and subsequently cooling) of the section rather than any differential heating of the steel wire along its length. However, more promisingly, when the exposed end was covered – in this case with several layers of masking tape – thermal imaging of the covered cut end was able to pick up an accurate impression of the duct, grout and strands, including areas of deficient grout.

Laboratory experiments show similar areas of promise, with tests being able to differentiate areas of deficient grout and discontinuities within a strand (1). *However, the masking effects of a metallic duct and surrounding concrete does not lend IRT to use beyond externally ducted structures at present, and even in these cases may require active heating of the strand, which must be exercised with caution to ensure damage to the tendon is prevented.*

Acoustic Emission Monitoring (AEM)

Principal use: Detection of wire breaks within a post-tensioned system

Potential use: Identification of location of wire break within post-tensioning system

Acoustic emission sensors are a typically long-term form of structural health monitoring for detecting active internal defects - in most cases the breaking of individual tendon wires within a strand or fatigue crack propagation within structural steel. Monitoring systems are connected at strategic locations with the sensors in direct contact with the structure, with connection back to a datalogger and power supply. Any audible signals received by the sensors are recorded as ‘Possible wire breaks’ (PWBs), which are then converted to ‘Confirmed wire breaks’ (CWB) by careful signal analysis. In some cases systems are able to detect wire breaks to within 100mm accuracy (13).

These systems can have significant costs associated, and being long-term systems those costs will continue to accrue over time. A key drawback to AEM is its inability to provide a picture of the structural condition at the time of install; only deterioration from that point onwards can be captured, potentially giving an unconservative indication of strand condition.

System accuracy has in some situations been questionable; For example on the M48 Severn Bridge, during intrusive investigations of the main suspension cables, known wire breaks (e.g. intentional breaking of wires for sampling purposes) were in some cases unreported by the installed systems, and conversely false positives reported (18). In other instances such systems can be an important tool in the arsenal; on the Hammersmith flyover an AEM system installed in 2010 recorded over 700 breaks within the first 3 years, with the pattern of breaks matching closely with the observed condition from previous PTSIs (3).

Radiography

Principal use: Detailed examination of duct, grout and strand for deterioration

Radiographic imaging is achieved by placing radioactive isotopes emitting X-ray or gamma radiation against a structure, and capturing the emitted waves on a film or computer plate placed on the other side of the structure. Variations in material density are highlighted in the processed image, which can highlight defects in both the grout and tendons to a high degree of accuracy. Clarity of the image produced is dependent on factors such as thickness of the structural medium, density of standard reinforcement present and strength of the radioactive emitter.

The health and safety implications of radiographic assessment cannot be underestimated. The isotopes themselves can be extremely hazardous – a concern that is worsened by the potential need for long exposure times (e.g. up to an hour) to obtain the necessary image in deeper sections, with a limiting depth beyond which meaningful results cannot be obtained. As such, significant exclusion zones are required for the use of X-rays, combined with additional shielding for any operators and areas used by the public. These factors alone can often leave radiography impractical, particularly if the structure is near to the area to be inspected.

In addition to the safety aspects, the practicalities of the tools can be equally limiting. As described above, the system requires an emitter on one face, and a carefully positioned plate on the opposite face, usually in the magnitude of 400mm square. The need for simultaneous access to both faces can be a logistical challenge made doubly difficult if the system is to be optimised by taking repeated images from multiple directions, thereby involving reversing the position of the equipment (13), (3). *Combining the small exposure area with the logistical challenges and the potentially extended duration to capture a single image, together with the health and safety needs means that in reality, radiography should be used in a targeted manner once the key areas of concern have been identified.*

Despite these drawbacks, radiography remains one of the best methods available for obtaining clear visual evidence of internal condition, including being able to identify section loss and voids within the grout.

Low-Frequency Ultrasonic Tomography (Shear-wave method using MIRA)

Principal use: Detection corrosion of tendons, bond quality and voids within ducts

One of the more cutting-edge tools for the assessment of internal post-tensioning ducts is ultrasonic tomography, typically using a MIRA device, akin to that used in medical science for ultrasonic scanning. This is a variation on the impact echo system with a “catch-pitch” system of transductors and receivers, with defects being detected by the pattern and timeframe of returned ultrasonic shear-waves. The system is in theory able to undertake thickness measurements, detect voids in concrete or ducts and detect poor-quality bond members (17) (3).

A MIRA device collects three planar images, known as B, C and D-scans. These produce 2-dimensional scans in the X,Y and Z planes, which can then be combined to form a 3-dimensional scan of the structural makeup. Varying frequencies can be used, with some literature indicating that lower frequencies may needed for deeper penetration within a member (16).

The system has been successfully used to detect cracks, spalling, rusted reinforcement and voids, and although the system is portable and does not rely on the operator having access to both sides of the structure, *it does require a flat section of concrete to apply the MIRA device to*. However, aside from this limitation, the device can be quickly moved from location to location by an experienced operator, which is made particularly easy due to the dry point contact transducers that negate the need for any coupling gel or surface preparation.

Common Intrusive SHM Technologies

There exist a number of intrusive technologies that have long-since been identified as key aspects of a structural health monitoring (SHM) system. These are outlined in the following section. Note that guidance on these technologies – in particular half-cell potential surveys - are set out in CS 465 – Repair and Management of Deteriorated Concrete Highway Structures (19) and the Inspection Manual for Highway Structures (20).

Half-cell potential surveys

Principal use: Identification of areas of corrosion risk

The use of half-cell potential surveys is tried-and-tested for normal reinforced concrete sections, whereby a cell is formed from exposed reinforcement and an electrode. Readings are taken in a grid, giving a potential map of the area, highlighting areas with the greatest risk of corrosion.

Although common for reinforced concrete, *the drawback for this technology is the need to expose the duct and tendon, making this form of survey more akin to a destructive technology rather than NDT*. However, it should be noted that as with the use of GPR for chloride monitoring (see below), even the development of a corrosion potential map within the reinforced concrete is a useful datum for the analysis of a post-tensioned system – particularly where metallic ducts have been used and there are known grouting voids or areas of low cover to the ducts.

Embedded Chloride Probes

Principal use: Monitoring of Chlorides within a concrete deck

Potential use: Wireless sensors for Chloride monitoring

The ingress of chlorides into concrete is a key component in the initiation of corrosion of reinforcement, steel post-tensioning ducts and therefore the strands contained within. Chlorides, usually from de-icing salts, reduce the alkalinity of the concrete which in turn helps to prevent steel corrosion. Once the chloride levels have reached a certain level, they will break the passivity protective oxide layer of the steel members, and in the presence of moisture and oxygen, corrosion will be initiated. Depending on the nature of the carbonation or chloride distribution, corrosion will either be in a generalised, widespread manner or through localised pitting (21).

Many sensor systems have been developed to measure corrosion, and specifically chlorides. In particular, linear polarization resistance (LPR) techniques have been found to be one of the most reliable and valuable methods for identifying the intrusion of chloride in concrete structures (22). The development of reliable, embedded (LPR) probes that can be left in-situ to return data on the changing condition of a concrete structure has been explored in a number of papers, with principle trials under laboratory settings, such as Lu and Ba in 2010 and Goa, Lu and Yang in 2011. In the latter, the embedded sensors were refined to a size of 10mm x 15mm.

Despite advances in sensor technology, there is still a practical aspect to the deployment of any embedded probes that must be addressed. Given that a probe will only return data on its immediate surroundings, by needs there must be a network of such sensors, usually deployed in a grid within a structure. However, there is an obvious balance that must be struck; cost and disruption due to installation (and upkeep) of a system versus breadth of coverage for any given structure. Specific research has been applied in this instance to enable the optimisation of a system using multiobjective optimisation, based on the available technology and the limitations therein (23).

Developments in these systems are now utilising wireless technology, and borrowing technology from other industries – in this case the use of wireless Chloride monitoring for agricultural applications – known as Aquatag, manufactured in the Netherlands – has been subject to laboratory trials for engineering use (24). *Although in this instance the system was trialled only in laboratory settings, the system showed reliable transfer of readings between the sensor and readout coil up to a separation of 35mm, making it feasible to embed within concrete structures. However, the impact of surfacing and other media has not yet been studied, and may well impact the reading reliability.* It should finally be noted that a significant advantage of the system is that no battery is needed to power the sensor terminal, making long-term embedment a viable option for this technology.

Electrically Insulated Tendons (EIT)

Principal use: Ensuring high construction tolerances for tendon grouting and ongoing monitoring of deterioration to PL3 Level

EIT is a methodology of encapsulating tendons and anchorages, fully electrically isolating them and giving the highest levels of confidence against moisture ingress and corrosion (25). This technology was first introduced and trialled in Switzerland (26), and more recently builds on the recommendations and testing requirements of Fib Bulletin 75 for Polymer-duct systems (27), using isolated anchorages and polyethylene or polypropylene, low-dielectric ducts, transition tubes and connectors, with heat-shrink sleeves to ensure water-tight seals. Indeed, EIT is one of the few technologies that can enable the highest Protection Level (PL3) advocated by the Fib Bulletin 75, enabling both leak-tight encapsulation and effective ongoing monitoring from construction.

A key process and benefit of EIT is the ability to measure the degree of corrosion protection during grouting, which can then be maintained as an SHM technique going forwards. Impedance measurements are taken at the anchorage locations, with physical connections to individual tendons, capturing ohmic resistance (R), capacitance (C) and the loss factor (D). The capacitance is constant for a specific tendon length, diameter and material, increasing proportionally with tendon length, whilst conversely the ohmic resistance (R) reduces with length. Through the measurement of R, C and D it is possible to determine the electrical isolation (and therefore the tightness of the duct along its length) at any time after the grouting (28). The system does not directly measure section loss, rather the presence of moisture within the grout, thereby indicating deterioration due to moisture ingress post construction.

Research into long-term monitoring of those structures with EIT has shown promising results; In the study by Elsener (26), at the time of reporting the six tendons of the Pré du Mariage flyover had been monitored for over eight years, with no indication that water (and by association chloride) ingress had occurred within the ducts. In a second example within the paper, a small, unnamed 22.9m long structure demonstrated a clear drop in resistance of a single tendon, indicating moisture ingress for this duct.

A potential limitation for this system is the as-yet undemonstrated long-term reliability of the monitoring; once a short circuit caused by a defect has occurred within the system (indicated by a drop in resistance), the system cannot immediately be used to identify where the issue is located. However, the impedance measurement connection enables developing technologies such as Magnetic Flux Leakage (refer to the next Section) to be effectively used to locate the location of lowest resistance – particularly if both ends of the anchorage can be accessed and electrically connected (26). *A potential issue with this approach is the site of lowest resistance may mask less severe defects (e.g. small holes within ducts).*

Clearly, a key limitation to this technology is for it to be used as a SHM approach the system must be designed and installed with EIT components; metallic or non-isolating duct materials are unlikely to be able to be effectively retrofitted with impedance monitoring systems.

Experimental and Developing Technologies

In addition to those tools, processes and systems described in the previous section, there are a number of technologies that are still in various stages of development (although it is acknowledged that all of the technologies are 'developing' to some extent). Some have existed for a number of years, and are only now maturing to a state whereby they can be of use within the field of assessment of post-tensioned structures, and others are very recent in development. This section captures some of the more promising technologies and where they have already been successfully employed or trialled.

Magnetic Flux Leakage (MFL)

Potential use: Detection of discontinuities and deterioration in tendon strands. Active MFL scanning for detecting large areas of corrosion, passive MFL for smaller, localised areas. May be coupled with EIT systems for more accurate readings.

Magnetic Flux Leakage is a measurement technique based on the application of a magnetic field in the vicinity of a ferromagnetic material (i.e. steel) to create magnetic flux lines to pass through the steel. Since the concrete is non-magnetic (unless there are impurities present), the magnetic flux remains in the strand or reinforcement. In the instance where there is a discontinuity such as corrosion or a broken wire, the magnetic flux is deviated and the leakage from the system is detected by the magnetic sensors (1). There are three forms of MFL, being active, residual and induced (known as IMF – refer to later section) which relates to the method of magnetising the specimen strand. In particular, it has been noted that active MFL has more use for identifying more widespread areas of tendon deterioration, whilst passive MFL has better capability for localised defect identification (29).

For in-situ measurements, the key challenges are encountered in the effect that a duct has on the readings and the impact of multiple layers of reinforcement between the sensor and the strands being studied. Despite this, MFL is a key methodology for detecting strand corrosion and local wire breaks in near-surface tendons, functioning for both metallic and HDPC ducts (3). It has been demonstrated by Azininamini (2017) that use of the active variant of MFL can be used in laboratory settings to clearly identify physical discontinuities within a strand, such as intentionally cut and separated strands - although the individual wire breaks cannot be identified within a group of strands. Furthermore, parametric testing coupled with detailed 2D and 3D Finite Element Modelling has shown promise in enabling the interreference from ducts and nearby reinforcement to be modelled, allowing for strand deterioration to be detected even in their presence. The use of electromagnets can further improve the system for field usage, but at present *this technology and the standard processes that are involved are still developing to enable the noise associated with 'real world' complications to be accounted for and the signals effectively analysed. Further limitations are it's focus on the strand alone within a duct – MFL will not identify grouting defects or moisture within the system – and the cumbersome nature of the equipment that may cause practical difficulties.* Despite these challenges, MFL is considered one of the most promising technologies for detecting strand deterioration within PT Tendons (29).

Chloride Mapping by Ground Penetrating Radar (GPR)

Principal use: Identification of Chloride levels within a concrete deck

The use of GPR to measure corrosion has been developing since the late 1990s, with field tests and laboratory studies to explore the potential for combining this inexpensive and versatile system with corrosion monitoring (21). The system relies on the variance of the electromagnetic (EM) wave within the concrete, which is a dielectric material, and specifically from the change in relative permittivity of the material due to the crystalline sodium chloride present when it is chloride-contaminated.

An experimental study by Hong (2015) proved that with GPR has the potential to visualise corrosion at an early stage, even before concrete cover cracked. In the field, this study indicated that the system worked for monitoring (i.e. measurement of deterioration from a baseline) rather than providing an absolute measure of corrosion. Regardless, the study also proved that the system could successfully map the chloride levels within the concrete, which is clearly a strong precursor for corrosion.

It is this system that has been built upon by the Swiss Federal Institute of Technology, which has been successfully deployed on bridge decks to provide a chloride 'heat map' for entire deck surfaces without the need to remove any surfacing other than for a small number of calibration cores (13). *The system is susceptible to the elements, and results can also be hindered by dense reinforcement, foil backed waterproof membrane or conductive content in construction materials.*

Clearly, this approach will not provide conclusive evidence of deterioration of a post-tensioning system, however it will give a clear indication if the *potential* for deterioration is in place, particularly if combined with metallic ducts with known voids and/or moisture is present.

Long-term Deflection Monitoring using Satellite Imagery

Potential use: Long-term deflection monitoring of bridge structures

Long-term studies into the deflection behaviour of bridges has been used to identify possible disorders at an early stage, enabling sufficient time to implement strengthening measures. One study in particular used extremely simple but effective hydrostatic levelling devices to monitor several swiss box-girder structures (totalling over 6000m of bridge length) of a 20 year period, beginning in the late 1980s (30).

The study showed that the balanced cantilever structures considered displayed an evolution of deflection at the mid-span over the periods monitored. In the case of the Paudeze Viaducts, this was a linear progression to +40mm over the years between 1988 and 2010, and over 160mm for the Lutrive viaducts over a much shorter period between 1973 and 1988. These viaducts were subsequently strengthened with additional post-tensioning to attenuate the deflection progression; In the case of the south viaduct this was repeated again in 2000 due to the continuation of the deflection trend.

Although a the 20-year study used a simple system of hydrostatics, the birth of high-resolution satellite imagery coupled with artificial intelligence (AI) and pattern recognition presents an opportunity to gather similar data to the Burdet study, but on a network of bridge structures simultaneously.

A study by Hoppe, et al., in 2019 presents a discussion of the technology required to undertake these works, using a TerraSAR-X radar satellite to monitor two post-tensioned bridges in Virginia, US. Satellites have already been used for the both micro and macro-monitoring of areas, typically for the detection of geotechnical faults such as subsidence, settlements or landslips. *For the monitoring of structures, the technology presents immediate challenges, such as the need (for short term monitoring) to account for environmental factors such as thermal heating and cooling of the structures*. These data can be accounted for if corroborated against local weather stations and monitoring, enabling millimetre-level accuracy – up to a nominal precision of +/- 5mm for any single measurement, and down to +/- 1mm for annual movements, highlighting that the readings are mitigated when long-term monitoring is undertaken (31).

In the case of the Hoppe, et al. study, the study was conducted only over the course of 15 months on two modern post-tensioned structures only 10 years of age. It is not unexpected in this case that the study did not determine any progressive movement of the structures; however, when combined with the findings of Burdet, the power of this research for network-level monitoring of structures quickly becomes apparent.

Digital Image Correlation (DIC)

Principal use: High-resolution, contactless measurement of strain and displacement

Potential use: Identification of sub-surface flaws

DIC is non-contact optical sensing technology that uses high-resolution digital imagery, tracking the relative position of individual pixels within images to determine sub-millimetre movements of actual points on a surface (32). Consequently, the system enables the remote mapping of strain on a surface, and in the case of the Dizaji et al. study, the creation of three-dimensional surface deformations with stereo-paired cameras.

The Dizaji et al. study considered the use of DIC to infer sub-surface defects based on surface-level strain discontinuities in differing materials through combined use with Finite Element Modelling. Although in its infancy, the research shows promise, and may provide a practical methodology for identifying areas of concern within a post-tensioned structure – potentially to be combined with further exploration by other means.

Beyond the study in Dizaji et al., the use of DIC for high-resolution, contactless deflection monitoring is becoming more sophisticated, with applications now in many structural uses (33). The technology facilitates the gathering of displacement data in many elements that were previously difficult or impracticable to monitor, such as bridge soffits on tall, long-span structures or over environments where access is restricted and/or costly (e.g. the rail network). There is no single explicit use of DIC for the monitoring of post-tensioned structures in this case, but it remains an impressive and versatile tool where movement is key; For example monitoring the progression of cracking following lines of post-tensioning ducts under live loading, or the relative displacement of a suspect deteriorated post-tensioned beam compared to its neighbours.

Electrical Capacitance Tomography (ECT)

Potential use: Identification of voids and moisture within external ducts

Electrical Capacitance Tomography is a technology that originates from the oil industry, used to reconstruct cross-sectional images of oil flow inside pipelines (34). In post-tensioning systems, its potential is in detecting both air and water-filled voids in ducts in HDPE ducts through the use of multielectrode sensors.

In the study conducted by Terzioglu et al., 2019, the use of ECT was limited to trials in external ducts, and even in this case its success was limited; It was in some cases able to identify both air and water filled voids, *however this was not consistently successful, nor was the system able to detect* *compromised grout nor the magnitude of captured grouts.* In theory this fast and safe system could be used to monitor the production of bleed water or voids during grouting in real time, but in practice the technology does not yet demonstrate sufficient consistency even for externally ducted situations.

Inductance Measurement Method (IMF)

Potential use: Measurement of section loss within tendon strands

A separate technology to MFL, Inductance Measurement exploits the ferromagnetic properties of the steel prestressing strands within a tendon, energising the system with an inductor (typically an alternating current). For internal post-tensioning tendons, a probe coil is placed on the concrete slab, which is then energised with the AC current. An expanding and contracting magnetic field links to the steel strands, and through measurement of inductance section loss within the tendon can be estimated (1). At present, although proof-of-concept exists for this technique, there is little field application and requires further refinement in order to become a viable NDT technology for field use (29).

In addition to the lack of field trials, a known limitation is the presence of reinforcement in the specimen – particularly transverse reinforcement – which can interfere with the inductance method, and as such can be a significant limitation for the adoption of this technology (1). However, these difficulties could be overcome through the use of laboratory baseline testing of samples without secondary reinforcement, which would enable section loss to be estimated in the field as it has been proven to be possible within laboratory settings.

Summary of Technologies

The systems and technologies presented in the previous sections represent the majority of NDT technologies that are available or under development within the market at present, together with a brief summary of their strengths and weaknesses with respect to post-tensioned structures. To aid in visualising the applicability of these technologies, a visual 'infographic' has been presented in Appendix A, demonstrating some of the key technologies that are being deployed or are in development with respect to their usage. In addition, a matrix has been prepared and presented in Appendix B, listing the technologies available and current understanding of where and how they may be applied. A Red/Amber/Green status has been implied against each technology and the various usages, again informing how well developed they are for that particular use; i.e. Red for 'could be developed for use in this area', amber for 'already has some capability for use in this area' and green for 'fully deployed and in use in this area'.

Identification of Key Technologies for Exploration

With regards to the technologies described in this paper, a number of different NDT approaches and embedded sensors tackling different aspects of post-tensioned structure deterioration have been identified. It is therefore recommended that further exploration of the effectiveness of a smaller number of the more promising technologies that will be of widespread use be taken forward for further consideration of trial and study. These include:

- Handheld sensor technologies (GPR and MIRA)
- Active and Passive Magnetic Flux Leakage (MFL)
- Low-Frequency Ultrasonic Tomography (MIRA)
- Wireless embedded Probes, such as Chloride and moisture
- Chloride mapping via GPR

- Satellite Imagery for long term deflections

As identified above, the importance of 'traditional' technologies such as embedded probes should not be undervalued; knowledge of ingress of Chlorides and moisture within a system, coupled with the presence of voids within ducts places a structure at a much more significant risk of post-tension deterioration. However even in these areas, the adoption of modern approaches to older technologies (e.g. wireless probes) may yield significant advantages for the future monitoring of our existing post-tensioned bridge stock.

Conclusions

In reviewing the available literature on NDT and embedded sensor technologies for post-tensioned bridges, it is clear that there does not yet exist a clear technology that provides a bridge owner a comprehensive understanding of the internal condition. Indeed, there does not yet exist a combination of NDT systems that can fully achieve this; all of the systems have inherent flaws, limitations and inaccuracies.

It is therefore still the widespread industry view that only through a combination of careful analysis, tailored NDT, embedded sensors and finally targeted intrusive testing can a full picture be achieved (17). Furthermore, there cannot even be identified one suite of tools and processes that can pointed to as best practice; The variation in post-tensioned structures in terms of both form and condition will mean that in each case an experienced engineer will need to make an informed decision on the best course of action, and will likely have to review and adapt that plan as new information becomes available.

A recommended approach would be to undertake further trials on a number of the emerging and established technologies in an in-situ trial, coupled with intrusive testing and numerical modelling to validate findings. The aim of such trials would be to home in on those technologies that are found to add value for real-life, in-situ structures, creating approved guidance on the current techniques and technologies that would benefit PT investigations where there are known criteria or areas of interest, similar to the infographic in Appendix A.

Establishing means of installing remote technologies in the more at-risk structures should be a priority, adopting structural health monitoring into the network to identify and proactively rectify poorly constructed or deteriorating tendons and ducts before they impact on service use. Clearly, technologies such as EIT should be strongly considered for any new constructions, enabling assurance on construction tolerance in addition to providing a ready means of future SHM, however this technology will not solve the problems of the existing stock of post-tensioned structures in the UK.

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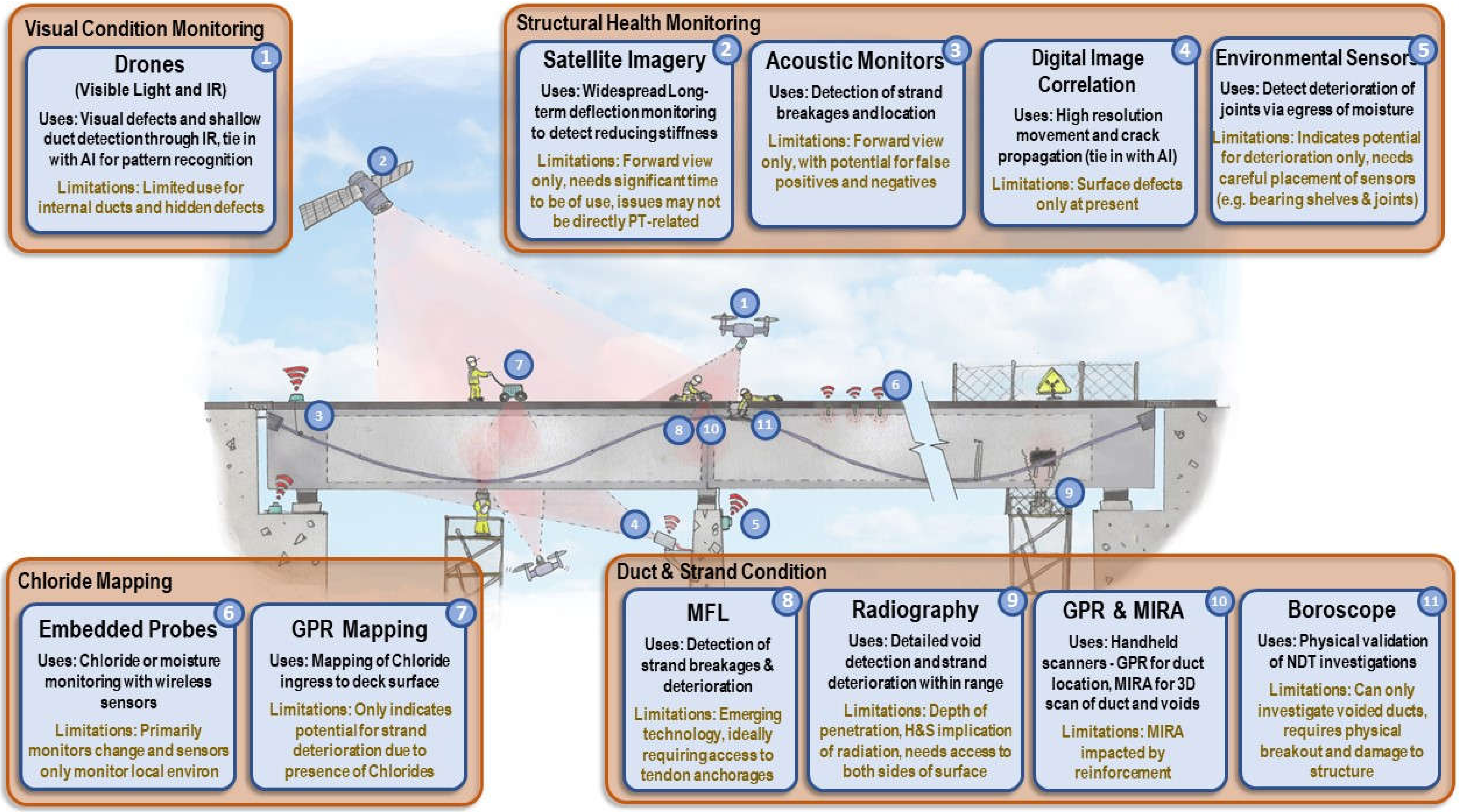
Appendix A – Technology Infographic



Appendix B – Technology Matrix

							Vision-Based											Scanning													Embedded Sensors											Physical Tests									Destructive Tests				
Structure Defect Areas	Defect	Total Potential Technologies		Red - Could be developed	Amber - Has some capability	Green - Currently deployed	DIC - Long Term	DIC - Short Term	DIC - Drone Mounted Survey	Drone Survey (Video/Photo)	Deflection Trend Analysis	Visual Examination	AI crack recognition	CCTV/Remote	Fibre Optic Video/Endoscope	LIDAR Scanning	Ortho-rectified images	Magnetic Particle Inspection	Magnetic Flux Leakage	X-Ray Radiography	Ground Pentrating Radar (GPR)	Chloride Mapping by GPR	Covermeter (Tendon/rebar location)	Directional Metal Detector	Infra-Red Thermography	Impact Echo (IE)	Ultrasonic Pulse Velocity (UPV)	Linear Polarisation Readings (NPR)	Low-Frequency Ultrasonic Tomography (MIRA)	Impulse Response	Physical Strain Guaging	Fibre Optic Strain Guage	Acoustic Emission	Drainage/Flow Monitoring	Accelerometers (NF measurement)	Moisture Probe	Load Cells	Chloride Probes	Resistivity	Half Cell Potential Testing	Relative Humidity Testing	Hammer Tap	Rebound Hammer Testing	Carbonation Testing	Permability of Concrete	Compressive Strength Assessment	Pressure-Vacuum Testing	Slot Cutting - Strain measurement	Access ports for inspections	Pull off testing on tendons	Strand cores/sampling	Water Jetting to expose tendons	Concrete Pull-off testing	Concrete Testing - Cores	Chloride Testing - Cores
Cracking	1) in post-tensioned concrete elements - various locat	15		2	2	10		R	R	A		G	A				G			G						G			G		G											G	G		G								G		
Water management system	1) cracks and potholes in carriageway surfacing;	11		2	0	9		R	R	G		G	G	G		G	G								G	G																											G		
Water management system	2) surface ponding on deck;	7		0	2	5				G		G	A				G																	A		G					G														
Water management system	3) blocked drainage systems;	6		0	1	5				G		G			G																			A		G					G														
Water management system	4) water trapped in boxes and other structure voids;	4		0	1	3									G																			A		G					G														
Water management system	5) damaged or missing deck joint seals;	9		1	1	7			R	G		G		G	G		G																	A		G					G														
Water management system	6) water leaks and staining on soffit and at movement	11		1	2	8			R	G		G	A	G	G	G	G																	A		G					G														
Deflection	1) excessive deflection;	9		1	2	6	A	G	R		G						A														G	G			G		G																		
Deflection	2) differential vertical deflection.	9		1	2	6	A	G	R		G						A														G	G			G		G																		
Concrete	1) delamination and/or spalling due to corrosion or fr	19		1	3	14			R	G		G	G				G			A	G				G	A			G	A								G				G	G		G								G	G	G
Concrete	2) spalling or crushing due to stress concentrations;	14		2	3	9		R	R	G		G	A		G		G			A						A					G	G					G											G						G	
Concrete	3) honeycombing;	14		1	1	12			R	G		G			G		G									A													G			G	G		G	G		G					G	G	
Concrete	4) evidence of chemical attack;	17		1	0	16			R			G			G		G					G														G		G	G	G	G			G	G	G			G				G	G	G
Concrete	5) low cement contents.	8		0	1	7																				A																G	G		G	G		G					G	G	
Reinforcement corrosion	1) visual evidence;	14		2	2	10	G	R	R	G		G	A		G	G	G			G	G				A																								G			G			
Reinforcement corrosion	2) evidence from corrosion testing.	10		0	1	9																A							G							G		G	G	G	G			G										G	G
Construction joints	1) leaks and stains.	11		2	1	8		R	R	G		G		G	G	G	G																	A		G					G														
Bearings	1) corrosion, deterioration and/or damage;	16		2	3	11		R	R		G	G		G	G	G	G														A			A	G	G	A	G			G														G
Bearings	2) unexpected movement/rotation or failure to move	10		1	2	6		G	R		G						A														G	G			G		A											G							
PT Defect Areas	Defect																																																						
Ducts	1) incorrect location;	11		0	2	9									G			A		G	G		G	G	A															G									G		G			G	
Ducts	2) corrosion;	16		1	0	15									G					G		R						G										G	G	G	G			G	G		G		G		G	G		G	G
Ducts	3) perforation;	7		0	1	6									G			A		G																											G		G		G	G			
Ducts	4) presence of water;	7		0	1	6									G											G								A		G					G				G						G				
Ducts	5) ungrouted.	12		1	2	9									G					G	A					G	A		G	R															G		G		G		G	G			
Grout	1) cracked or shattered;	7		0	0	7									G					G						G			G																	G	G		G						
Grout	2) soft;	8		1	0	7																			R	G										G									G	G	G		G					G	
Grout	3) moist;	8		1	0	7																			R	G										G					G				G	G			G					G	
Grout	4) voids;	13		1	3	9									G					G	A				A	G	A		G	R															G	G	G		G					G	
Grout	5) low cement contents;	3		0	0	3																																							G	G								G	
Grout	6) high chloride and/or sulfate contents.	7		1	2	4																R																G		A	A					G								G	G
Tendons	1) incorrect type or size;	13		1	6	6		A			A				G			A	R	G															A				A	A									G	G	G	G			
Tendons	2) missing tendons;	12		1	5	6		A			R				G				A	G															A				A	A									G	G	G	G			
Tendons	3) corrosion resulting in loss of section;	21		1	6	14		A			A				G				A	G		R						A	G		G	G			A	G		G	A	G	G								G	G	G	G			G
Tendons	4) fracture of wires/strands/tendons;	13		0	4	9		A			A				G				A	G											G	G	G		A														G	G	G	G			
Tendons	5) loss of prestress.	9		0	5	4		A			A																				G	G			A		G												A	G	A				
Anchorages	1) deterioration of capping material.;	16		0	3	13						G	A		G					G	A				A													G		G		G	G	G			G		G				G	G	G
Anchorages	2) moisture/water;	12		0	2	10									G										A	G										G		G		G	G				A				G		G			G	G
Anchorages	3) high chloride and/or sulfate contents in capping ma	10		0	3	7																G																G			A			G					A	A	G		G	G	G
Anchorages	4) corrosion;	15		0	3	12									G					G		A														G		G		G				G	A		G		G	A	G	G		G	G
Anchorages	5) missing anchorage components	5		0	2	3									G					G	A																													A				G	
Green - Currently Deployed							1	3	0	10	4	14	2	5	25	5	12	0	0	15	3	2	1	1	2	9	0	1	7	0	8	7	1	0	4	15	4	11	4	8	14	5	5	6	12	9	8	4	17	5	12	9	8	18	11
Amber - Has some capability							2	5	0	1	4	0	6	0	0	0	3	3	3	2	4	2	0	0	5	4	2	1	0	1	1	0	0	8	5	0	2	0	3	3	2	0	0	0	2	0	0	0	2	3	1	0	0	0	0
Red - Could be developed							0	6	14	0	1	0	0	0	0	0	0	0	1	0	0	3	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	Potnetial Applications						6	14	14	11	9	14	8	5	25	5	15	3	4	17	7	7	1	1	9	13	2	2	7	3	9	7	1	8	9	15	6	11	7	11	16	5	5	6	14	9	8	4	19	8	13	9	8	18	11