WORK PACKAGE 9: PRACTICAL BRIDGE MANAGEMENT

Task 9.6 – Interface with Current Practice

D9.6.1 - Report on Actual Practice in Bridge Management

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Preface

This report is a deliverable from the Growth Thematic Network "Structural Assessment, Monitoring and Control" (SAMCO), which was initiated in October 2001.

The present report constitutes the deliverable D.9.6.1 *"Interface with current practice"* under task 9.1 "Report on actual practice in bridge management".

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ROLE OF MONITORING IN BRIDGE MANAGEMENT

1. INTRODUCTION

Bridges form a vital part of the infrastructure within which we live. From the humble footbridge to a major structure carrying a multi-lane lane highway bridges permit a safe means of overcoming natural or man-made obstructions to our journey. The design, construction and maintenance of bridges are becoming increasingly complex as new techniques and materials have become available. The considerable resources associated with such works require that the bridge should continue to operate safely throughout its service life and in many instances for much longer periods of time. To achieve this requirement in a structured and methodical way bridge management procedures have been developed.

Bridge management procedures, such as BridgeMan (2001), must fully address the four key stages in the life-cycle of a bridge. These are:

- Design
- Construction
- In-service (operation)
- Demolition.

The objective is to construct and maintain bridges in a safe condition whilst keeping them available for use both now and in the future, also to maintain the value of the asset and, minimise damage to the environment and the use of natural resources. Preventative maintenance will increase the life a structure and reduce or eliminate the need for major intrusive maintenance actions. Its disadvantage is that it needs to be applied to all structures before it is known which structures are subject to rapid deterioration and this is clearly expensive. However, monitoring procedures that identify early stages of deterioration can establish those structures or parts of a structure that would benefit most from preventative maintenance thereby making it more selective and cost effective.

Monitoring techniques can play an important role in detecting the onset, and monitoring the development of any deteriorating mechanisms throughout the life of a bridge; e.g. they can be used to locate and analyse defects thereby permitting an informed structural assessment to be made, and subsequent decisions about whether or not repairs are needed (also the extent and type of repair). The various applications for which monitoring can be used are summarised in Table 1. Monitoring devices may also be used to confirm (or not) assumptions made during design, for example the measurement of construction and/or in-service loads on a structural element. Such data can lead to improved designs and more cost efficient economic structures.

When considering setting up a monitoring scheme, it is essential to be very clear about the end requirement, i.e. what is expected to be determined from the ensuing data. Such a process can not be started to early as some devices may only installed during construction as access may be impossible at a later date. Another crucial point to consider is the duration of the monitoring period.

Rate(s) of deterioration may be obtained from measurements recorded consistently over a long period of time. Such information enables informed estimates to be made of the future condition of the parts of the structure monitored, and is essential when deciding the necessity and urgency of repair work; thus such work is a significant aid to the planning and budgeting of maintenance work.

In summary, effective monitoring can be used to provide early warning of deterioration that could affect the fabric of the structure in the future. This would enable preventative maintenance work to be carried out before significant deterioration has occurred, and thus it could also form part of a selective preventative maintenance strategy.

This report considers how monitoring techniques can be used as part of a bridge management strategy and provides a framework for the SAMCO Thematic Groups. The range of applications for the different monitoring techniques, and for different types of bridges are summarised in Table 1 for the four key stages in the life-cycle of a bridge: design, construction, in-service and, demolition.

A list of the monitoring devices considered in this report is presented in Table 2, also presented are the stage of the development of the device and the application for which it is intended.

A full description of each monitoring technique is presented in the Appendices to this report, with examples of its application and identifies sources of additional information. For simplicity a consistent format has been used: the format is summarised in Table 3.

2. BRIDGE MONITORING

The installation of a monitoring device onto a structure generally relies on surface mountings; these may be permanent fixtures or be a part of a 'mobile' survey where the sensors are moved to separate locations around the structure. In some instances holes or cavities may be made in the bridge or one or more of the structural elements to allow the installation of a device, but the act of doing this may in itself have an unknown affect on the parameter that you are trying to measure. In other cases it might be physically impossible to get to the desired location. Therefore it can be advantageous for monitoring to be considered at the design stage, permitting monitoring devices to be installed on a structural element or within the structure itself before construction is completed.

2.1 Sensors at fixed locations

The advantage of sensors applied at the time of construction is that they provide a good indication of temporal variations from the time of construction and can normally be monitored remotely either at a convenient location adjacent to the structure or in the office. A limitation is that it may only feasible to investigate a relatively small part of the structure; however, this can be mitigated by considering the risk of deterioration in different positions and locating them at positions which are both structurally critical and most subject to deterioration.

Sensors generally provide an early warning of deterioration so that there is enough time to carry out a wider range of survey tests over a greater proportion of the structure to confirm the sensor results and establish the extent of deterioration before serious damage has time to develop.

2.2 Measurement surveys (movable sensors)

Survey tests, using mobile testing equipment, can be carried out at any time but they usually require access and may result in some disruption to traffic. They can only give temporal variations of measurements if the surveys are repeated a few times. However, they do permit a much greater area to the structure to be investigated than that allowed by sensors. Furthermore a wider range of tests can be performed, the combined results of which, are usually easier to interpret in engineering terms than measurements from sensors.

There is also the question of the life of sensors in comparison with the life of a highway structure. Experience of the use of sensors is quite short and although some have performed well for about 10 years there must be some doubt whether they will perform satisfactorily after 50 or 100 years. Most deterioration processes on highway structures develop at a comparatively slow rate so infrequent repeat measurements are generally sufficient indicating that testing surveys are sufficient to evaluate the rate of deterioration.

Long-term installations require high quality cables that do not perish and their positioning also requires careful consideration to ensure that they are not vulnerable to vandalism. It is important to ensure the back-up power supplies are available in the event a power failure. Good quality measurement cabinets should also be used both for security and to protect the measuring equipment for the environment ie extremes of temperature and humidity.

In summary, both monitoring techniques, i.e. fixed sensor locations and measurement surveys, have their own specific advantages and limitations. A balanced combination of both approaches will provide the greatest benefits to the structural engineer.

2.3 Assessment of data

When analysing and assessing recorded data, it is important to differentiate between measurements that provide an *instantaneous* picture of the structural condition and those that are measuring a *cumulative* effect.

An instantaneous measurement is one where the value corresponds to a particular instant in time e.g. ambient temperature. A cumulative measurement records what has happed over a time interval e.g. the amount of electric charge passed as recorded by a domestic electricity meter. Both types of measurement have their advantages and instantaneous measurements can be converted to cumulative if they are monitored continuously and the areas under their time graph calculated. Most measurements are instantaneous although cumulative ones are often more useful; e.g. electrical resistance corrosion sensors record the mean level of corrosion (metal loss) that occurs in a time interval and this is more useful than knowing the corrosion current density (rate) at a particular time.

Some tests can be regarded as screens in the sense that large areas of a structure can be covered quite quickly but the quality of data generated is relatively low. These tests are useful if they can reliably confirm the absence of deterioration and approximately locate sites of possible deterioration that can be investigated by more detailed methods.

The accuracy of test data is sufficient for most purposes, but the interpretation of results can be far from clear. Single tests provide limited and often indirect information. Generally it is only by combining the results from a range of tests that a reasonable engineering interpretation can be made.

2.4 Terminology

Unless specific measurements are being considered, confusion and misunderstanding can arise when discussing levels of deterioration because the qualitative assessments and personal perceptions are different for every individual. In an attempt to mitigate the potential for such problems it is suggested that the definitions provided in the United Kingdom Highways Agency Advice Note BA 79 (1998) are adopted as standard; the definitions cover aspects such as *sub-standard structures* and *risk*.

The Advice Note covers the safe management of highway structures which are found to be sub-standard. In particular the AN provides guidance on the followings topics.

- Assessment process
- Interim measures during assessment
- Interim measures after assessment pending strengthening
- Monitoring
- Prioritisation for strengthening

3. BRIDGE MONITORING THROUGHOUT THE LIFE CYCLE

Bridge management (and monitoring) is a continuous process that commences at the concept stage and applies throughout the four key stages of the existence of the bridge. This Section of the report describes the benefits of undertaking a sustained programme of monitoring, and the benefits that can be accrued from such works.

3.1 Design

The standards used in bridge design, have in the past, essentially been are based on experience gained in the construction of previous bridges and on tests undertaken both in the laboratory and on bridges in-service; latterly complex computational methods have also been used.

Monitoring the performance of bridges can provide a very important in put to the development of design codes and to check that structural behaviour is in accordance with the designers' assumptions. However, monitoring is not used routinely for this purpose but tends to be restricted to special structures e.g. cable-stayed bridges, novel designs and, where new materials or techniques are being used.

Monitoring may also be used to measure actions on structures for use in future designs; examples of such actions are loadings due to wind, temperature and traffic.

3.2 Construction

Monitoring as part of the construction process is largely concerned with ensuring that the structure is built to specification. This includes checking the level and alignment of the structure and the forces in the load bearing elements, monitoring the grouting of post-tensioned structures and checking concrete strength.

Monitoring systems are sometimes installed during construction to provide feedback for design as described above or to determine the long-term performance of the structure and enable deterioration to be detected at an early stage. There are however, only a small number of bridges where monitoring systems have been installed during construction.

3.3 Service Life

The main purpose of monitoring during service life is to detect and monitor deterioration as summarised below:

- the detection of hidden deterioration e.g. wire fracture in post-tensioning or hanger cables
- the prediction of when deterioration is likely to occur in order to assist the prioritisation of future maintenance operations, and provide predictive information for bridge management systems rather than reacting to problems as they occur: e.g. monitoring ingress of chlorides into reinforced concrete
- checking structures where deterioration or damage has occurred and it is necessary to ensure that there is no further loss in strength

1. checking structural adequacy to give advance warning of increase in the risk of collapse (e.g. on "sub-standard" structures that do not appear to be suffering distress.)

- checking bridges at specific risk such as structures over water that might be subjected to scour.

Monitoring techniques that enable the condition of bridges to be monitored remotely for purposes such as those listed above, could have a useful role and this represents the main market for monitoring. However, there are hundreds of thousands of highway bridges throughout Europe, so monitoring techniques either need to be very economic or focus on particular types of structure or structures with specific problems. Therefore the requirement for monitoring can be divided into two groups:

i) techniques that use low cost sensors that can be easily installed and monitored, have a long life and are cost effective i.e. they provide information that is required by the engineer and that would be more expensive to obtain by other means.

ii) monitoring systems that can be used on major structures or on structures that have particular problems e.g. where there are concerns about their condition and monitoring enables them to remain in-service.

In both cases, it is necessary to demonstrate that it is more cost effective to monitor than to take alternative courses of action.

3.4 Demolition

Demolition of complex structures is a specialist task, and there are occasions when it is necessary to monitor the structure as it is demolished. A good example of just such a task was the demolition of a multi-span post-tensioned bridge over the Afon Taff, at Taff Fawr, Wales (UK). The bridge was taken down by reversing the construction process. This required careful monitoring of the stresses in the structure to guard against sudden collapse and to ensure the safety of the demolition workers.

4. BRIDGE MONITORING FOR RESEARCH PURPOSES

Occasionally structures may be monitored for reasons unconnected with their management, but for other reasons such as obtaining data for research purposes. This may be to provide feedback to design codes or to evaluate the effectiveness of new materials or the form of structural elements. It is equally possible a structure may be used to proof test or validate a new monitoring technique; or it may be trialled alongside established techniques.

5. THE OWNERS PERSPECTIVE

It is important that any monitoring of in-service structures should be undertaken with the full approval, and wherever possible the collaboration, of the owner the bridge or their representatives. Such actions ensure that the maximum benefit may be obtained from the monitoring programme by both all parties, and sources of useful and relevant documentation are available to all. Some items that might be considered prior to setting up a monitoring scheme are provided below.

- Aim of the monitoring programme
- Who the scheme will affect
- General description of the scheme
- Approval of the programme
- Description of monitoring schedule
- An understanding of how the data may be used
- Monitoring period

6. CONCLUDING REMARKS

The monitoring of highway bridges is not routinely undertaken. However, a well designed and implemented programme may accrue significant benefits for the industry and the owner of the bridge. The benefits may include,

- better understanding of durability and performance
- more accurate structural assessments
- improved understanding of how the structure behaves
- improved design procedures

- assistance in the prioritisation of maintenance operations leading to a reduction in maintenance costs

There are a wide range of monitoring devices, and monitoring systems, that are commercially available on the market today. In addition specialised companies exist who can provide advice, or undertake monitoring programmes for simple to complex schemes.

The analysis of data and assessing the interaction of different deteriorating agencies is complex, and should not be undertaken lightly or by inexperienced staff; expert advice should be sought.

There is a market for monitoring techniques where it can be shown that they are cost effective and lead to an overall reduction in the costs of operating and maintaining the structure.

Bridge owners have a vested interest in structural assessment monitoring and control, but such persons may not be aware of the range of knowledge and expertise that is available to help them manage their stock. Lack of informed management inevitably leads to expense for the owner and delays and inconvenience for the user. It is hoped that reports such as this will promote better bridge management.

7. REFERENCES

BridgeMan (2001). BridgeMan: a management system for maintaining bridge stock. Version 2. TRL Software Bureau. TRL Limited, Crowthorne.

Design Manual for Roads and Bridges. The Stationary Office, London.

BA 79 (1998). The management of sub-standard highway structures. (DMRB 3.4.18)

TABLE 1: BRIDGE MONITORING TECHNIQUES

Part of the Bridge Life Cycle	Bridge Type	Monitoring objective	Techniques
Design	All special structures	Feedback to design codes Check assumptions made in design	All
	Concrete bridges	Long-term corrosion behaviour	Sensors Corrosion potential Macro-cell Resistivity
Construction	Post-tensioned bridges	Loss of pre-stress Cable tension	Glass fibre strain sensor Strain sensors
	Suspension and Cable Stay	Movement damping	Control systems
	Concrete bridges	Carbonation and chloride ingress Self healing of cracks and corrosion	Corrosion cell Self injecting chemical
	Steel bridges	Fatigue crack initiation and progress	Ultra-sonic
	Masonry bridges	Water ingress	Electrical conductivity
	Flexible footbridges	Vibration and damping Seismic risk	Accelerometers & time domain analysis
In-service	All above		
	Bridges over water	Scour Impact of floating debris, boats & ships	Visual inspection Impact sensors
	Heavy traffic	Weigh in motion Load measurement at supports	Load or strain sensors Electrical (load cells)
	Bridges with low clearance or slender support	Vehicle/train collision	Impact and/or displacement sensors
	Bridges with cantilever support (half joints)	Fatigue crack (steel) Shear crack (concrete)	Ultra-sonic
	Sub-standard bridges o Low risk o Medium risk o High risk	Periodic monitoring (deflection, overall movement) Frequent instrumented monitoring (strain, cracks) Continuous monitoring (strain, cracks, loading, other risk factors)	Displacement or vibration Ultra-sonic
Research	All	To evaluate new techniques for monitoring the corrosion state of pre-stressed and post-tensioned wires.	New techniques
Demolition	All, particularly continuous bridges, post tensioned bridges	Loss of stability Explosive collapse	Deformation & displacement

TABLE 2: LIST OF MONITORING TECHNIQUES AND THEIR APPLICATIONS

Technique	Stage of development	Application
Embedded reference electrode for potential measurements	Routine	Assess risk of corrosion of steel in reinforced concrete.
Macro-cell for time to corrosion monitoring	Routine	Determine onset of corrosion of steel in reinforced concrete
Concrete resistivity measurement	Routine	Evaluate the state of corrosion of reinforcement in concrete.
Electrical resistance probe	Specialist (routine)	Determine the onset of corrosion and estimate the rate of corrosion in reinforced concrete bridges.
Electrochemical noise	Specialist (routine)	Local pitting corrosion and assessing its severity in reinforced concrete bridges.
Potential mapping	Routine	Evaluate the state of corrosion of the reinforcement of concrete bridges.
Carbonation	Routine	Prediction of future corrosion behaviour of reinforced concrete.
Chloride profile	Routine	Determines the penetration of chloride ions into concrete.
Corrosion rate	Routine	Estimate rate of corrosion .
Infra-red thermography	Under development	Detection of defects beneath a concrete surface.
Magnetic flux leakage	Under development	Assessment of the condition of tendons and hangers, and the corrosion of steel plates .
Impact echo	Specialist (routine)	Identification of defects within a beam, column or slab.
Acoustic emission	Specialist (routine)	Location of cracks in steel or concrete.
Ultra-sonic testing	Routine	Detection of internal discontinuities e.g. laps, seams, voids.
Ground penetrating radar	Routine	Evaluate the properties and geometry of sub-surface features.
Vibration measurement	Specialist (routine)	Monitoring of the integrity of a structure or structural element.
Optical fibre strain gauges	Specialist (routine)	Measurement of changes in strain in concrete structures..

TABLE 3: INFORMATION REQUIRED FOR EACH MONITORING TECHNIQUE

1. Details of the technique

- Principle of Application
- Accuracy (this may be difficult to define)
- Applications
- Advantages
- Limitations
- Equipment and procedure (including information on suppliers/web sites)

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2. Details of application

- Description of application (when and how to use)
- Accuracy
- Applications
- Advantages
- Limitations
- Equipment and procedure
- Interpretation
- Examples (Brief description, NOT a detailed case study)
- Standards/specifications (if available)

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3. Sources of further information

APPENDIX: A

Design
Long-term Behaviour

Design
Long term corrosion behaviour
Sensors: 1. Embedded reference electrode for potential measurements

1. Details of Technique

1.1 Principle of Application

In principle, the measurement of the so-called “corrosion potential” Ecorr, i.e. the spontaneous potential of the rebar, may give an indication of its state of corrosion. Some specification states that there are definite ranges in which different state of corrosion can be identified:

- Ecorr > -200 mV (vs. CSE, saturated copper/copper sulphate electrode): no corrosion
- Ecorr < -350 mV (vs. CSE): corrosion
- Ecorr between –200 and –350 mV (vs. CSE): uncertain

Therefore, the installation of reference electrode inside the concrete should be specified at the design stage, in order to have the possibility, during the service life of a structure, of having a direct response on the corrosion behaviour of the reinforcement.

The potential ranges given are those quoted in the ASTM standard. They are however sensitive to

- Moisture content of the concrete.
- Type of corrosion – localised or general.

Since the reference cell is buried in the concrete the resulting potential measurements should be less sensitive to variations in moisture content than reference cells applied at the surface since it is mainly the surface 25mm layer of concrete that experiences major variations in moisture content.

If the corrosion is of the localised (pitting) type then it is unlikely that discrete embedded sensors, covering only a small part of the structure, will locate anodes. Furthermore discrete embedded sensors will not be sufficient for calculating the potential gradients, that are used to assess which type of corrosion is occurring.

A step reduction in potential of the sensor of about 200mV, that is maintained over time, is a good indicator that the passive film has been broken down.

The result of the measurement is just the value of the corrosion potential (in mV) vs. the reference electrode used. Since the specification, as already said, usually are referred to the SCE (Saturated Copper/copper sulphate Electrode) it is important to know the potential values of the reference electrodes used (vs. the Standard Hydrogen Electrode), which are the following:

- Copper/copper sulphate +316 mV
- Silver/silver chloride +199 mV
- Manganese dioxide +365 mV

1.2 Accuracy

The accuracy of the measurement is very high: an error of ±20 mV is usual and acceptable.

1.3 Applications

The application concerns the long term corrosion behaviour of the reinforced concrete bridges exposed to aggressive environment.

1.4 Advantages

The measurement of the corrosion potential may promptly indicate the passage from the passive to the active state of the reinforcement.

The use of an embedded reference electrode in a structure does not need measurements on-site, since it can be connected to a long distance monitoring system, where it can be possible to follow day by day the evolution of the corrosion.

Potential changes are slow so the benefits of continuous measurement from a sensor are small. Periodic surface potential mapping is probably a better option since larger areas can be covered, provided that obtaining access does not cause major problems. This appendix should cross reference to 'In-service Potential Mapping' section so the user can compare these two options for potential measurement.

1.5 Limitations

Only a limited number of reference electrodes can be embedded in a structure at the construction stage (for economic reasons) and therefore only those points deemed to be at risk can be instrumented with such sensors. It is not possible to know the corrosion state of the other parts of the structure, even if the overall corrosion behaviour may be rather clear.

Environmental conditions (temperature – humidity) can influence the potential values, thus leading to erroneous interpretation of the results.

The ranges suggested by the ASTM specification are not fixed. They strongly depend on the environmental condition of the structure exposure and on the concrete quality.

Normally corrosion of reinforcing steel in highway structures takes from about 10 – 40 years to initiate. It is therefore important that the life of the reference cell sensor should exceed 40 years. This is a demanding requirement and the sensor track record is not long enough to give a view of their long term durability.

1.6 Equipment and procedure

Even if the values of the potential are usually referred to the CSE (Saturated Copper/copper sulphate electrode), the most reliable electrodes which can be embedded in concrete are actually:

- Silver/silver chloride
- Manganese oxide

The Silver/Silver chloride electrode is normally supplied as a silver rod in a silver chloride paste in a solution of saturated or 0.5 molar potassium hydroxide.

The manganese dioxide reference electrode, that has become very popular, is supplied as a manganese dioxide paste on a graphite base in a solution of 0.5 molar potassium hydroxide solution, with a cementitious plug as contact to the concrete

Suppliers include:

- Silver/silver chloride Farwest (www.farwst.com) SSS Korrosionsschutztechnik (www.sss-kt.de)
- Manganese dioxide: Germann instruments (www.germann.org) SSS Korrosionsschutztechnik (www.sss-kt.de)

The technique requires the use of a high impedance voltmeter that may be obtained from suppliers of research technical equipment

Reference cells recommended can certainly be purchased 'off the shelf' and are accurate and stable. Copper sulphate cells should, however, not be disregarded, although they are less accurate, they can be easily 'home made' in a simple laboratory and their robustness is well suited to site use.

2. Application

2.1 Description of application

The application of corrosion potential sensors is suitable for structures destined to be built in aggressive environments.

The number and location of the sensors must be decided at the design stage. The embedment of the reference electrodes must be made at the construction stage. The measurements will be carried out at pre-defined suitable time intervals.

2.2 Interpretation

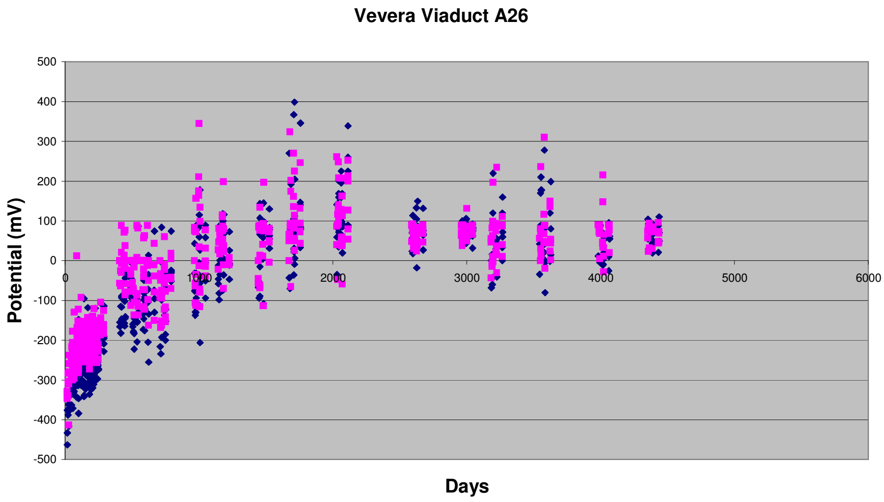
The practical experience on a large number of structures shows that the results of potential measurements need careful interpretation in order to determine correctly which areas of the structure are corroding. It has been found that there are no absolute values of potential to indicate corrosion risk in a structure, in contrast to the interpretation given in the ASTM that relies on a fixed potential value of –350 mV CSE

2.3 Examples

Potential measurements in 60 locations of a viaduct in Northern Italy are shown in the following figure:

It can be seen that the passivation of the mat after the construction needs more than one year to be reached.

During the following 11 year passivation is maintained even in presence of heavy de-icing salts strewing.



2.4 Standards/specifications

ASTM C876-91

Design
Long term corrosion behaviour
Sensors: 2. Macrocell for time-to-corrosion monitoring

1. Details of Technique

1.1 Principle of Application

Pieces of metals with different potentials can be coupled together as galvanic macrocells, so that either the potential difference or the electrical current between the anodes and the cathodes can be measured. The potential difference and the current intensity are proportional to the iron dissolution.

The simplest macrocell consists of two pieces of reinforcing bar, one located at the rebar level and the other in a much deeper position. As soon as both become passive (the steel needs a certain time, sometimes more than one year, to reach a good situation of passivity) there is no potential difference or passage of current. When the aggressive agents (carbon dioxide or chlorides) reach the reinforcements and corrosion starts immediately the potential difference or the current intensity will rise.

To monitor the distance from the concrete surface in which the reinforcement is no longer protected by the concrete, sets of bar pieces can be placed in the concrete at different depths; a piece of metal that does not corrode (stainless steel, titanium) is installed near the steel pieces. As long as the electrical current between the steel pieces and the noble metal are in the range of the typical currents for passive state, i.e. very small, neither ingress of critical chlorides nor carbonation has reached the position of the outer piece of steel. As soon as it happens, the current will rise significantly. In the course of time the next piece of bar will be depassivated and so on, allowing monitoring the critical depth permanently.

The measurements may be made either directly on site or with connection to a remote centralized p.c. The variations of potential difference and current intensity are put in evidence on a graph.

1.2 Accuracy

The accuracy of the system is very high, since very small variations of the corrosion state of the piece of bar under control give a sharp increase of the potential difference and of the current, therefore indicating the sudden initiation of corrosion.

1.3 Applications

The application concerns the long term corrosion behaviour of the reinforced concrete bridges exposed to aggressive environment:

1.4 Advantages

The use of macrocells may promptly indicate the passage from the passive to the active state of the reinforcement. The multi-electrode sensor allows the determination of the time-to-corrosion of the rebar.

1.5 Limitations

Usually a limited number of macrocells are embedded in the structure at the construction stage (for economic reasons) and therefore only the most individuated critical points can be equipped with such sensors. It is not possible to individuate the corrosion initiation in the other parts of the structure.

The system is very sensible and therefore the alarm may be a too early alarm. Nevertheless, the knowledge of corrosion initiation can be the starting point for supplementary investigation in the following years.

1.6 Equipment and procedure

Commercial sensors may be purchased from:

- Germann Instruments, Corrowatch (www.germann.org)
- S+R Sensortec, Anode-Ladder-System (www.sensortec.de)

2. First Application

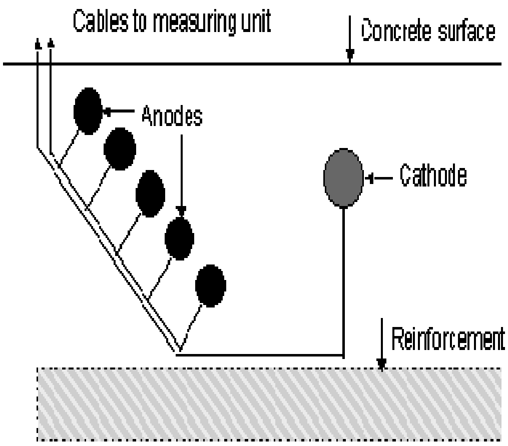
2.1 Description of application

The application of macrocell sensors is suitable for structures destined to be built in aggressive environments.

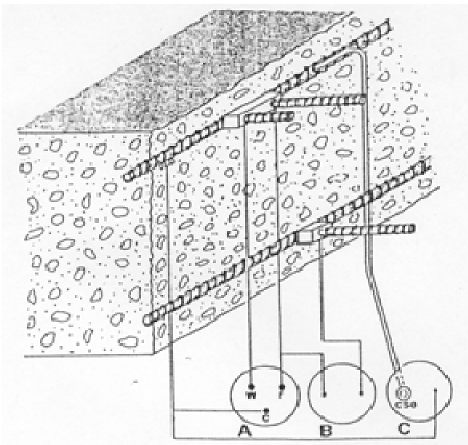
The number and location of the sensors must be decided at the design stage. The embedment of the macrocell must be made at the construction stage. The measurements will be carried out at pre-defined suitable time intervals.

2.2 Equipment and procedure

The sensors are very simple and look like in the following figures. The cables must be connected to a high impedance voltmeter or to an ammeter. The readings are also very easy and may be made directly by automatic devices.



Anode-ladder-system



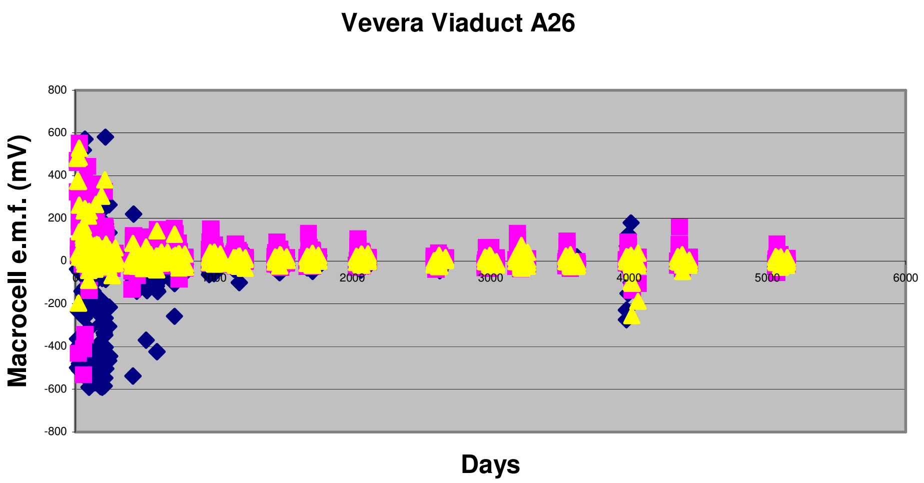
Two electrodes macrocell (B)

2.3 Interpretation

The interpretation of the results does not need a great experience, since it is based on the sharp increasing of either the potential difference or of the current intensity. It is a qualitative means of monitoring the corrosion initiation.

2.4 Examples

Potential measurements in 90 locations of a viaduct in Northern Italy are shown in the following figure:



It can be observed that at the beginning there are many locations with a rather high potential difference (emf); this potential difference tends to decrease, due to the passivation of both pieces of bar, and remains very low even after twelve years, sign of no corrosion initiation.

Design
Long term corrosion behaviour
Sensors: 3. Concrete resistivity measurement

1. Details of Technique

1.1 Principle of Application

The electrical resistivity of concrete is a property which may be useful for monitoring and inspection of concrete structures with regard to reinforcement corrosion.

Besides the chemical composition of the pore water on the pore structure, the resistivity of concrete depends on the moisture content, on the temperature, on the chloride concentration, etc., and may vary by several orders of magnitude, from 10 to 10^5 Ω*m.

The resistivity is determined by measuring of the electrical resistance using a traditional resistance bridge.

The value of the resistivity, expressed in ohm*m is recorded for every monitored location of the structure where the sensors are embedded.

1.2 Accuracy

The accuracy depends on the scale; it may be of the order of 10% of the end-scale.

1.3 Applications

The application concerns the long term corrosion behaviour of the reinforced concrete bridges exposed to aggressive environment.

1.4 Advantages

The measurement of the concrete resistivity may indicate the passage from the passive to the active state of the reinforcement.

The resistivity of a given structure gives information about the risk of early corrosion damage. After damage occurs, resistivity is relevant to the maintenance strategy as well: electrochemical repair technique (chloride removal, re-alkalization, cathodic protection) are influenced by resistivity.

1.5 Limitations

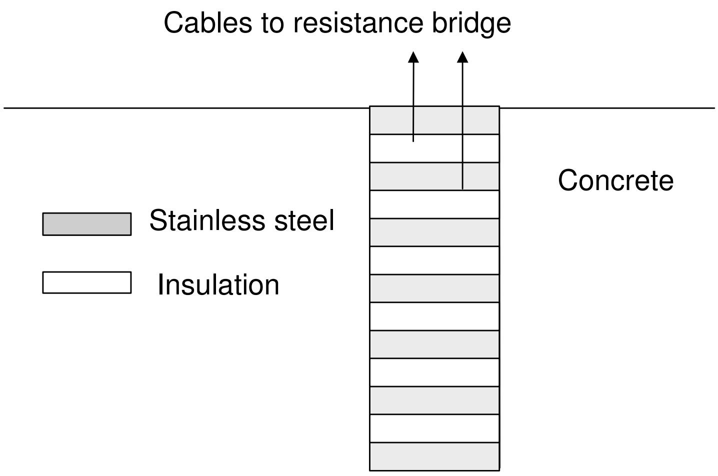
Usually a limited number of resistivity sensors are embedded in the structure at the construction stage (for economic reasons) and therefore only the most individuated critical points can be equipped with such sensors. It is not possible to individuate the corrosion initiation in the other parts of the structure.

Environmental conditions (temperature – humidity) can influence the resistivity values, thus leading to erroneous interpretation of the results.

1.6 Equipment and procedure

The multi-ring electrode is a special type of sensor that can be used for monitoring the resistivity of the concrete at different depth (S+R Sensortec, Multiring electrode (www.sensortec.de))

The sensor consists of several stainless steel rings isolated by plastic rings as shown in the following figure. Connection to each of the stainless steel electrodes enables the resistance between pairs of neighbouring rings to be measured.



Multiring electrode

2. First Application

2.1 Description of application

The application of resistivity sensors is suitable for structures destined to be built in aggressive environments.

The number and location of the sensors must be decided at the design stage. The embedment of the probes must be made at the construction stage. The measurements will be carried out at pre-defined suitable time intervals.

2.2 Interpretation

In the corrosion circuit, the ion transport rate, which is related to the resistivity, is one of the corrosion rate controlling. Therefore, from the electrochemical nature of the corrosion process, a relation is expected between concrete resistivity and the reinforcement corrosion rate after depassivation. Using a simplified approach, the corrosion rate of depassivated steel in concrete may be supposed to be inversely proportional to the resistivity. In any case, it appears certain that within a given structure areas with low resistivity will have a relatively high corrosion rate respect to the areas with high resistivity.

There is nowadays a general agreement on the correlation between the resistivity of the concrete and the level of corrosion of the reinforcement

Level of corrosion	negligible	low	moderate	high
Resistivity Ω*m	>1000	1000-500	500-100	<100

Appendix A
Design
Long Term Corrosion Behaviour
Sensors:4 Electrical resistance probes

1. Details of technique

1.1 Principle of Application

This technique is based on the increase in electrical resistance that occurs when the cross section of the steel probe is reduced by corrosion. The resistance of the corroding probe is measured relative to that of an identical probe that is protected from the corrosive environment. This protected probe should experience the same temperature changes as the corroding probe because this will simplify the compensation of resistance changes due to temperature variations. An AC resistance bridge makes the resistance measurements.

Electrical resistance probes are normally sited in the concrete cover zone to provide an early warning of reinforcement corrosion problems on the structure. Alternatively a network of probes can be designed to track the corrosion process as chloride ions or carbonation penetrate the concrete.

Electrical resistance probes measure the cumulative metal loss on the probe rather than the instantaneous corrosion rate. This is useful because it enables measurements to be made infrequently without problem, although for most structures the probe will give null readings for many years before corrosion initiates. The probe therefore requires durable manufacture. A disadvantage is that after corrosion initiation a number of readings over a significant time interval will be needed in order for the rate of corrosion to be assessed.

There is a trade off between the life and sensitivity of an electrical resistance probe. The thinner the cross section of a probe the more sensitive it is, but the shorter is its life. For example the most sensitive probes are typically about 0.1mm thick making them sensitive to a metal loss as small as 10µm. General corrosion rates of steel in concrete are about 50µm per year so probes of this thickness would have a short life after the onset of corrosion. The probes can give a direct reading of metal loss in micrometres (µm).

A recent development is the inductive resistance probe that operates by a similar principle to the electrical resistance probe but offers greater sensitivity and a measure of instantaneous corrosion rate in units of $mA.m^{-2}$.

1.2 Accuracy

The accuracy of an electrical resistance probe will be about -/+ 0.01 x probe thickness hence a probe of sufficient accuracy can be found for most applications.

1.3 Applications

The application concerns the long-term corrosion behaviour of reinforced concrete structures exposed to corrosive environments.

1.4 Advantages

The electrical resistance probe provides an early warning of corrosion initiation on the structure and subsequently an estimate of metal loss and rate of corrosion. The probe does not need to be connected to the reinforcing steel. The probes can be designed to provide the required combination of sensitivity and life. The probes directly measure loss of metallic section and repeat measurements at different times enable the calculation of corrosion rate. Unlike electrochemical techniques, electrical resistance probes function satisfactorily in the presence of non-conducting deposits and are therefore effective for detecting under scale corrosion.

1.5 Limitations

Electrical resistance probes can not reliably detect pitting corrosion since a pit can penetrate the probe material without much change in resistance measurement if the area of the pit is small compared with the probe area. Most electrochemical methods suffer from the same limitation.

The presence of rust on the probe surface can lead to erroneous results.

Commercially available probes and monitoring equipment are relatively expensive, limiting the number of probes that can be used and the proportion of the structure than can be monitored. This is a limitation of most methods that rely on probes embedded in the concrete.

Electrical resistance probes typically give null readings for many years before corrosion is initiated and must therefore be of durable manufacture.

1.6 Equipment

Electrical resistance probes and monitoring equipment are supplied by Rohrback Cosasco (USA) and Cormon (USA). The primary application of the equipment is in the chemical process industries but they can be adapted for use in concrete structures and Rohrback supplies a probe dedicated to this purpose.

2. Application

2.1 Description of Application

The application of electrical resistance probes is suitable or structures to be built in corrosion environments. The number and positioning or probes must be decided at the design stage and the embedding of the probes must take place during construction. The measurements will be carried out at infrequent intervals until corrosion initiation is detected and then more often.

2.2 Interpretation

Electrical resistance probes are constructed of mild steel similar but not identical to reinforcing hence a loss of thickness and corrosion rate of the probes can only provide an estimate of the corrosion of the actual reinforcement. If the probes are positioned at the same level as the reinforcement they will provide a real time estimate of the corrosion parameters. If they are positioned closer to the concrete surface they will provide an early warning of corrosion on the structure and an estimate of its corrosion rate once corrosion of the structure begins.

2.3 Examples

There are few examples of electrical resistance probes being used for monitoring reinforcement corrosion in concrete structures. Zivica (2000) reported the application of an improved probe design in a 20-probe installation to monitor corrosion on a bridge in Prague, Czech Republic. The probes had been in service for 9 years at the time of the report (2000) when no significant corrosion had been detected.

Electrical resistance probes have also been used in research on reinforcement corrosion (TRL).

3. Sources of Further Information

Basheer, P.A.M., Gilleece, P.R.V., Long, A.E. and McCarter, W.J. (2002). Monitoring electrical resistance of concretes containing alternative cementitious materials to assess their resistance to chloride penetration. Cement and Concrete Composites, Vol. 24, pp.

Zivica, V. (2000). Utilisation of electrical resistance method for the evaluation of the state of steel reinforcement in concrete and the state of its corrosion. Construction and Building Materials, Vol. 14, pp. 351-358.

Appendix A
Design
Long Term Corrosion Behaviour
Sensors: 5 Electrochemical Noise (EN)

1. Details of Technique

1.1 Principle of Application

Electrochemical Noise is the random fluctuation in potential and current that occurs during an electrochemical reaction such as the corrosion of steel.

Noise measurements can indicate the type of corrosion damage that is occurring such as general or localised corrosion. The severity of pitting corrosion can be estimated from the frequency and shape of the noise curves (potential –time curves). A combination of potential and current noise measurements can estimate the rate of corrosion using linear polarisation resistance (LPR) theory. The measurements provide an instantaneous assessment of the corrosion state.

1.2 Accuracy

The technique is highly sensitive and is normally used qualitatively to distinguish between general and localised corrosion and to detect pitting and stress corrosion cracking. When it is used in a quantitative sense it only provides a rough estimate of, for example, corrosion rate.

1.3 Applications

The application concerns the long-term corrosion behaviour of reinforced concrete structures situated in corrosive environments.

1.4 Advantages

The main advantage of Electrochemical Noise is that it is one of the few methods that can detect and measure localised corrosion, such as pitting and stress corrosion cracking. It can provide an estimate of the rate of pitting. It generally performs well in media of low conductivity such as concrete. In practice electrochemical noise is used to study localised corrosion whereas the linear polarisation resistance method is used for general corrosion.

1.5 Limitations

The monitoring equipment is complex and costly limiting the application of the electrochemical noise technique. The interpretation of noise measurements is difficult and requires experience and skilled personnel.

1.6 Equipment

Commercially available Electrochemical Noise systems are manufactured by:

- Corr International, USA – SmartCET system
- CAPCIS Systems, UK – Concerto system

Both these systems are designed for corrosion monitoring in the oil and gas industries where the instantaneous assessment of pitting corrosion provided by electrochemical noise is used to control the dosage of inhibitors. There are few reports of its application to concrete structures although it has been used for research in this field.

2. Application

2.1 Description of Application

The application of Electrochemical Noise sensors is suitable for structures situated in corrosive environments. The technique normally uses sensors embedded in the concrete although like the linear polarisation resistance technique it is feasible to carry out the measurements on the reinforcing steel in the structure. Normally the number and positioning of the sensors must be decided at the design stage of the structure and installed during its construction. The probes are similar to those used for linear polarisation resistance measurements and it is possible to use the same probes for both methods. The LPR measurements provide information about general corrosion and the EN measurements about localised corrosion.

2.2 Interpretation

The interpretation is based on the shape of the potential – time and current – time transients. The interpretation is difficult and requires experienced and skilled personnel.

2.3 Examples.

There are no examples of the routine application of electrochemical noise to reinforced concrete structures but there are a number of research applications in this field and given the ability of this technique to assess localised corrosion its wider use deserves consideration. Research papers of interest are given in the following section.

3. Sources of Further Information

Katwan M.J., Hodgkiess T.; Arthur P.D.(1996). Electrochemical noise technique for the prediction of corrosion rate of steel in concrete. Materials and Structures, Vol. 29, pp. 286-294.

Legat, A., Leban, M. and Bajt, Z. (2004). Corrosion processes of steel in concrete characterized by means of electrochemical noise. Page 74 of 81 DRAFT 1 – December 2005 Electrochimica Acta, Vol. 49, pp. 2741-2751.

Krumbach, R. and Konig, G. (1998). Hydrogen-induced stress corrosion of prestressing steels - introducing a new testing method. 2nd PhD Symposium in Civil Engineering, Budapest, Hungary.

Tullmin, M.A.A, Hansson, C.M. and Roberge, P.R. (1996). Electrochemical techniques for measuring reinforcing steel corrosion. Corrosion 96, NACE, Denver, March 24-29, USA. Also at InterCorr/96, 1st Global Internet Corrosion Conference, 1996. [www.corrosionsource.com].

APPENDIX: B

In-service Corrosion Risk

Appendix B
In-service
Corrosion risk
Potential mapping

1. Details of Technique

1.1 Principle of Application

Potential mapping is the most simple electrochemical technique used for obtaining corrosion information on site. The technique informs qualitatively on the corrosion risk of the reinforcement.

The measurement is obtained measuring the potential difference between the rebar and a reference electrode. In the following table the potentials of the most common reference electrodes are reported.

Electrode	Symbol	Potential vs SHE
Copper/copper sulphate sat.	CSE	+0.318 V
Calomel (Hg2Cl2) sat.	SCE	+0.241 V
Silver chloride sat.	SSE	+0.199 V

In concrete structures the measurement is achieved by placing the reference electrode on the concrete surface. The value obtained is not the "true" potential of the metal because the reading may be affected by the presence of the concrete cover, however it is considered to represent with a good approximation the potential of the bar.

1.2 Accuracy

Each measurement has an accuracy of ±20 mV

1.3 Applications

Evaluation of the corrosion state of the reinforcement of concrete bridges exposed to aggressive environment.

The results may be given either as a table, showing the potential values in the various positions of the structure, or in coloured figures in which the colours represent different ranges of potential.

1.4 Advantages

Possibility of localisation of corroded areas reducing maintenance costs

1.5 Limitations

Corrosion potential limits often depends on the environmental conditions and concrete quality.

1.6 Equipment and procedure (including details of suppliers/web sites)

Canin, Proceq (www.proceq.ch)

2. Application

2.1 Description of application

After a certain time of years from the construction (ex.10 years) the Potential Mapping can describe the corrosion state of each component of the bridge including the bridge deck even in presence of the bituminous overlay

The measurements should be repeated after a period of 2-5 years in order to evaluate the evolution of the corrosion state of the reinforcement.

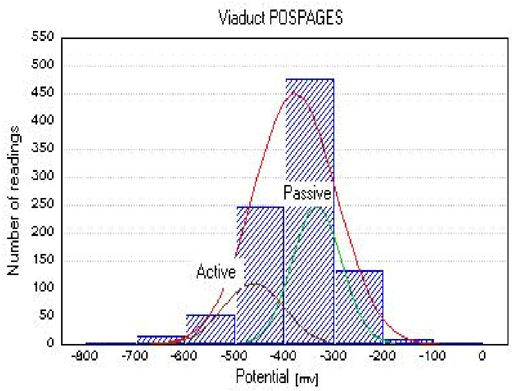
2.2 Interpretation

In potential mapping the first important thing to look at is the variation (gradient) of the potentials.

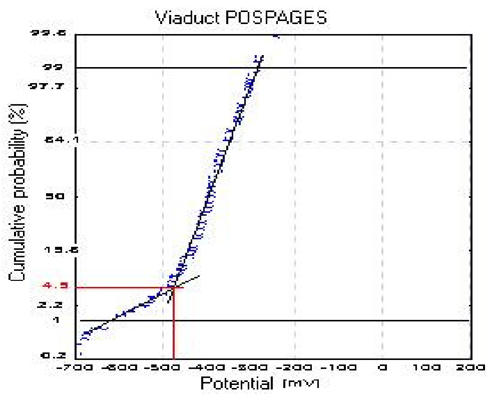
A change of 150-200 mV in the values show a change in the corrosion conditions of the bars moving from passive to more active areas where the values are more negative.

The ASTM standard relies to a fixed value of -350 mV (measured versus CSE) as a value that indicates the beginning of corrosion risk but it has been clarified that there are no absolute values indicating corrosion because the potential depends on several factor as moisture and chloride content, temperature, carbonation, concrete cover thickness etc.

When the survey concerns large areas and the mapping is obtained collecting a great amount of measurements a statistical analysis of the values can be made.



Gaussian plot of the results of a mapping



Plot of the potentials versus potential the number of readings

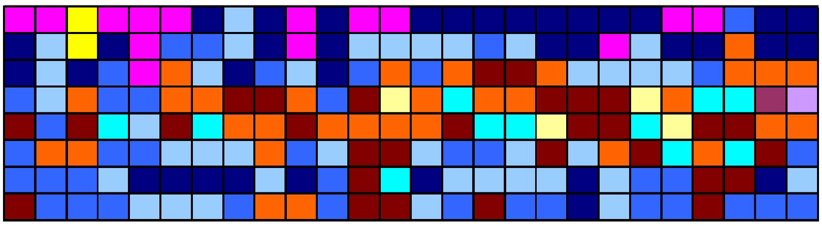
The potential values can be plotted versus the number of readings; this plot gives the information about the amount of passive and active potentials obtaining the frequency distribution. Assuming that active and passive areas both exist in a structure showing a normal distribution around a mean value two Gaussian curves can be fitted to the experimental value.

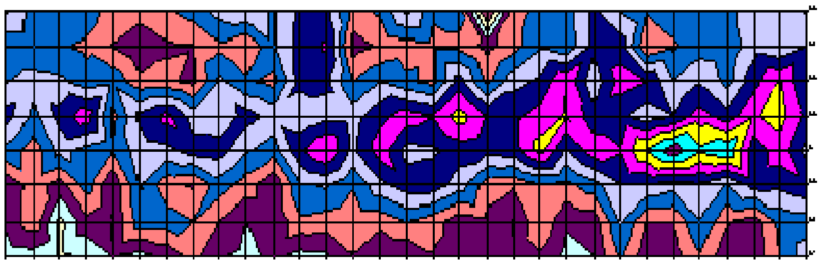
All data can also be plotted to obtain a cumulative probability representation; the sum of potential readings below a certain potential is plotted versus the potential on a special statistical paper.

2.8 Examples

The representation of the results looks like the following figures.

-180	-212	-268	-204	-186	-212	-181	-189	-248	-205	-206	-245	-215	-213	-203	-244	-186	-199	-309	-215	-220	-297	-210	-209	-300	-373
-325	-325	-300	-250	-200	-205	-289	-277	-261	-265	-301	-272	-217	-237	-197	-295	-206	-218	-356	-250	-250	-347	-255	-223	-312	-325
-353	-263	-244	-327	-275	-203	-342	-356	-305	-385	-428	-429	-376	-272	-255	-295	-282	-329	-396	-395	-368	-387	-347	-416	-413	-441
-375	-385	-420	-423	-355	-324	-441	-505	-386	-478	-380	-391	-422	-414	-430	-520	-393	-478	-454	-553	-632	-559	-589	-416	-480	-385
-410	-467	-376	-357	-421	-381	-353	-381	-375	-437	-476	-452	-524	-446	-439	-469	-504	-419	-414	-365	-398	-473	-419	-494	-519	-438
-262	-266	-231	-362	-308	-284	-417	-410	-298	-349	-311	-284	-421	-286	-382	-409	-499	-365	-472	-450	-349	-397	-331	-432	-503	-398
-212	-242	-247	-288	-250	-340	-421	-455	-228	-257	-274	-286	-288	-233	-282	-343	-307	-413	-427	-248	-291	-327	-313	-380	-352	-401
-272	-296	-320	-375	-395	-340	-412	-411	-278	-312	-413	-309	-320	-220	-274	-319	-324	-407	-343	-306	-335	-301	-318	-401	-366	-345





2.9 Standards/specifications (if available)

ASTM C 876-91: Half cell potentials of reinforcing steel in concrete

Appendix B
In-service
Corrosion risk
Carbonation

1. Details of Technique

1.1 Principle of Application

Either cores or freshly broken fragment may be used for the test.

The carbonation depth is determined by spraying a freshly broken surface of the sample with a 1% alcoholic solution of phenolphthalein; if the surface becomes a purple colour, it indicates that the pH is still high enough to protect the reinforcement. If the concrete surface remains uncoloured, the pH has decreased to values below the range usually corresponding to corrosive environment.

The depth of the carbonated concrete layer is measured and the carbonation depth, in mm, is recorded for each position where the samples have been taken.

1.2 Accuracy

An accuracy of 1 mm may be easily reached.

1.3 Applications

It may be applied to all aerial structures.

1.4 Advantages

The knowledge of the carbonation depth allows the prediction of the future corrosion behaviour of the reinforcement, since there are carbonation rate laws by means of which one can determine the correct time of maintenance and the risk of corrosion of the reinforcement.

1.5 Limitations

There are no limitations

1.6 Equipment and procedure (including details of suppliers/web sites)

The usual equipment used to extract cores, or a good hammer (example: that used for the rebound Schmidt test or for the pull-out test).

A 1% alcoholic solution of phenolphthalein, prepared by any chemical laboratory.

2. Application

2.1 Description of application

Depending on the environmental conditions (latitude, altitude, humidity, etc.) the test may be carried out after 5 to 10 years from the construction. It may be useful to repeat the test at least every 5 years during the first 15 years, and then every 2 years

2.2 Accuracy

The test is very easy, intrinsically accurate; besides, much care must be taken in the selection of the sites for sampling, since the local exposure (e.g. sun or shadow, near the soil or not, etc.) may be very important.

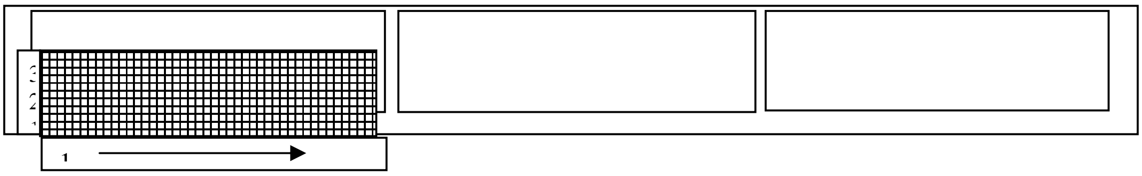
2.3 Interpretation

The knowledge of the carbonation depth does not necessarily give, by itself, a complete picture of the corrosion state of the reinforcement, and should therefore interpreted in the context with other techniques related to the corrosion of the rebar.

Nevertheless, whenever the carbonation has reached the reinforcement, its corrosion starts and the risk of corrosion exists.

2.4 Examples (Brief description, NOT a detailed case study)

The following example concerns a beam of a bridge approximately 25 years old. It can be observed that the carbonation depth is still rather low (12-18 mm).



CARBONATION -
mm

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
3										16										16					
2																									
1					18					12										14					

Appendix B
In-service
Corrosion risk
Chloride profile

1. Details of Technique

1.1 Principle of Application

When the concrete cover is cracked or spalling, the specimens (fragments) may be taken for chemical analysis.

Alternatively, the concrete can be drilled to various depths, separating each powder sample for all pre-determined depths.

Analysis of these samples, carried out by a chemical laboratory, will give a chloride profile. The chloride concentration is given as a percentage of the concrete weight.

The chloride profile, in weight percent by weight of concrete, is given for each position where the samples have been taken.

1.2 Accuracy

The accuracy of the results is usually of ±0.1%.

1.3 Applications

It may be applied to all aerial structures where there is a risk of penetration of chlorides (seaside, use of de-icing salts) in order to determine the risk of corrosion of the reinforcement.

1.4 Advantages

The knowledge of the chloride profile allows the prediction of the future corrosion behaviour of the reinforcement, since it is possible to establish the diffusion rate of the aggressive ions with a reasonable approximation.

1.5 Limitations

The technique causes some damage to the structure and the concentrations recorded can vary significantly over a small area.

1.6 Equipment and procedure (including details of suppliers/web sites)

The usual equipment used to extract cores, or a good hammer or driller.

2. Application

2.1 Description of application

Depending on the local conditions (vicinity to the sea, winds, temperature, frequency of de-icing salts strewing, presence of impermeable membranes, etc.) the first application may be carried out after 5 to 10 years from the construction.

It may be useful to repeat the test at least every 5 years during the first 15 years, and then every 2 years.

2.2 Accuracy

Sampling is very easy, intrinsically accurate; besides, much care must be taken in the selection of the sites for sampling, since the local exposure may be very important. The chemical analysis of the samples must be carried out by qualified laboratories

2.3 Interpretation

The knowledge of the chloride profile does not necessarily give, by itself, a complete picture of the corrosion state of the reinforcement, and should therefore be interpreted in conjunction with other techniques related to the corrosion of the rebar.

Nevertheless, when the chloride concentration is, at the reinforcement level, above certain values (approximately 0.06% related to concrete weight), it can be assumed that there is a risk of corrosion.

2.4 Examples

Chloride profile determined in cores sampled in different bridge components

Element	Cl weight% by weight of concrete	Depth (cm)
A	0.222	0 – 2
	0.173	2 – 4
	0.107	4 – 5.5
B	0.036	0 – 2
	0.025	2 – 4
	0.020	4 – 6
C	0.027	0 – 2
	0.161	2 – 4
	0.093	4 – 6
D	0.092	0 – 2
	0.040	2 – 4
	0.030	4 – 6

Appendix B
In-service
Corrosion behaviour
Corrosion rate

1. Details of Technique

1.1 Principle of Application

The corrosion rate is defined as the amount of metal loss due to corrosion per unit of exposed surface during a certain period of time (ex.: mdd, mg/dm^2*day). As concern the reinforcement bars, it is convenient to transform, using the density of the metal, this unit in loss of thickness (µm/year), hence in decrease of radius, or, doubling, decrease of diameter.

The actual techniques used in practice for the measurement of the corrosion rate of the rebar embedded in concrete are based on an electrochemical principle: they measure the actual corrosion current density (µA/cm^2) and, through the Faraday's laws, they give directly the thickness loss in µm/year. 1 µA/cm^2 corresponds, for carbon steel, to 11.6 µm/year.

The corrosion rate, in µm/year, is given for each position of the structure components, selected for the measures. It is possible to carry out a corrosion rate mapping, i.e. a co-ordinated campaign of measurements which can put in evidence the areas more prone to the corrosion attack.

1.2 Accuracy

The commercial equipment usually give the results with a great number of figures, but it is reasonable to define in two figures the accuracy of the measurement of the corrosion rate; low corrosion rates should be for example expressed as 0.78 or 1.2 µm/year, while high corrosion rates should be for example expressed as 9.2 or 12 µm/year. Further figures are meaningless.

1.3 Applications

It may be applied to all aerial structures where there is a risk of penetration of chlorides (seaside, use of de-icing salts) in order to determine the risk of corrosion of the reinforcement.

1.4 Advantages

The knowledge of the actual corrosion rate of the rebar allows the calculation of the residual life of a structure which suffers corrosion: the diameter loss corresponds to the formation of a volume of corrosion products (rust) easily calculable and therefore it is possible to evaluate the time when spalling will initiate.

Moreover it is possible to intervene with maintenance as soon as the corrosion rate reaches values which show a too rapid consumption of the bars.

1.5 Limitations

The corrosion rate which is measured at a certain time is "actual"; this means that it is not possible to extrapolate the value for the past and for the future. The value of the corrosion rate strongly depends on the conditions of the structure (humidity, temperature) and therefore it may be influenced by these factors. Repeated measures may give more reliable results.

1.6 Equipment and procedure

Commercial equipment is available from:

- Gecor (Geocisa, Spain) www.geocisa.com
- Galvapulse (Germann Instruments) www.germann.org

2. Application

2.1 Description of application

The measurement of the corrosion rate may start as soon as the structure has been constructed: the results obtained in the first years may be interesting for the knowledge of the variations in time and for a valid evaluation of the corrosion propagation.
It may be useful to repeat the measurement rather often, for example every two years.

2.2 Limitations

The technique cannot be applied when the rebar has no more concrete cover.

2.3 Equipment and procedure

2.4 Interpretation

The interpretation of the results should be made by specialists with experience.

The corrosion rate values can be used for the following purposes:

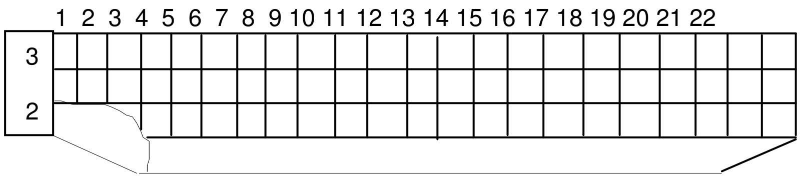
- To identify the locations with high corrosion activities
- To predict future deterioration
- To calculate the structural consequences of the corrosion (assessment of residual life)

The possible correlation between corrosion rate and level of corrosion is the following:

Attack penetration (μm/year)	**Corrosion rate ($\mu A/cm^2$)**	**Corrosion level**
< 1	< 0.1	Negligible
1 - 5	0.1 - 0.5	low
5 - 10	0.5 - 1	moderate
>10	> 1	high

2.5 Examples

The following example concerns a bridge approximately 25 years old. It can be observed that the corrosion rate strongly depends on the position where the measurement was taken, certainly due to the possibility of leakage of de-icing salt solution from the joints.



Corrosion rates, in $\mu A/cm^2$ for an element.

3	5,4	2,9	3,4	2,7	2,4	1,9	6,1	8,6	5,4	4,0	4,7	3,3	8,3	16,0	10,3	2,9	1,6	3,0	2,2	3,1	2,4	
2	0,7	0,6	0,2	0,6	2,7	2,5	8,9	11,7	4,1	6,0	4,2	8,1	13,8	27,3	11,8	5,0	9,8	2,0	3,9	7,8	1,9	
1				1,0	3,1	7,0	34,4	3,8	5,9	22,6	11,3	12,7	30,2	33,7	13,5	11,0	12,6	2,1	2,9	4,8	6,7	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22

2.6 Standards/specifications (if available)

RILEM TC-154-EMC: “Electrochemical Techniques for Measuring Corrosion in Concrete”

Appendix B
In-service
Corrosion risk
Concrete resistivity measurements

1. Details of Technique

The technique is described in Appendix A. Some applications to structures in service are described below.

2. Application

2.1 Description of application

The application of resistivity sensors is suitable for existing structures exposed to aggressive environments. The embedding of the probes is performed by making a core in the concrete and embedding the probe by means of mortar.

The measurements are carried out at pre-defined time intervals.

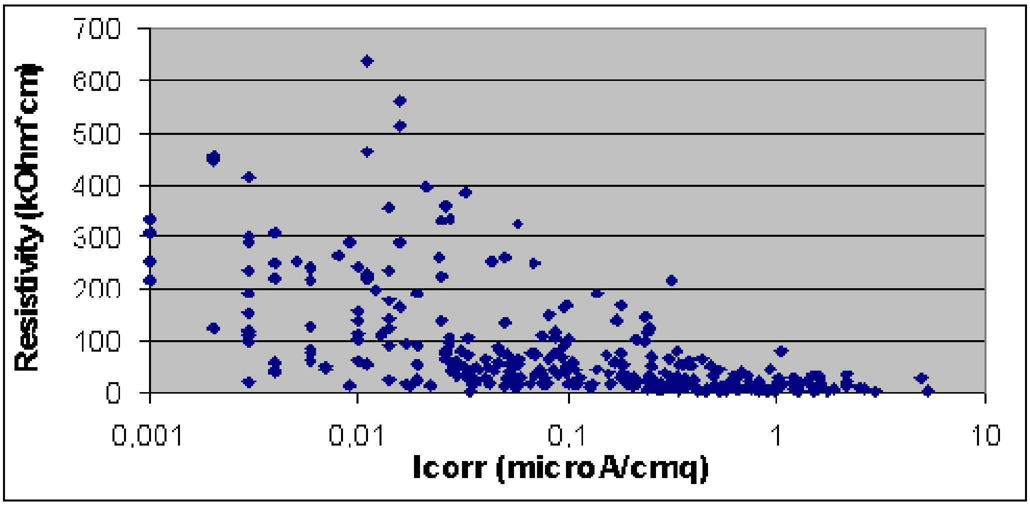
2.2 Interpretation

In the corrosion circuit, the ion transport rate, which is related to the resistivity, is one of the corrosion rate controlling. Therefore, from the electrochemical nature of the corrosion process, a relation is expected between concrete resistivity and the reinforcement corrosion rate after depassivation. Using a simplified approach, the corrosion rate of depassivated steel in concrete may be supposed to be inversely proportional to the resistivity. In any case, it appears certain that within a given structure areas with low resistivity will have a relatively high corrosion rate respect to the areas with high resistivity.

There is nowadays a general agreement on the correlation between the resistivity of the concrete and the level of corrosion of the reinforcement:

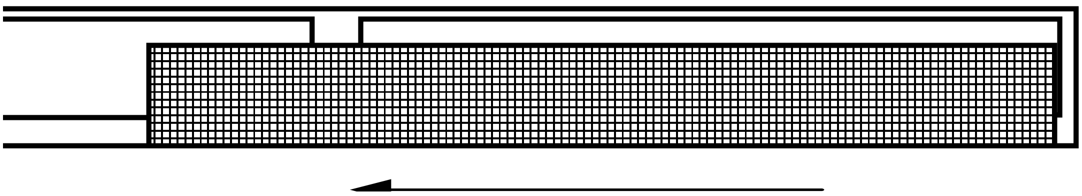
Level of corrosion	negligible	low	moderate	high
Resistivity Ω*m	>1000	1000-500	500-100	<100

The following figure shows the correlation between resistivity of the concrete and the corrosion rate measured in several components of bridges 25-30 years old.



2.2 Examples

The following example concerns a beam of a bridge approximately 25 years old.



	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
3	115,3	88,8	59,8	60,6	70,4	66,7	123,6	66,1	67,5	47,7	146,2	51,4	62,9	56,7	13,2
2	55	44,1	39,4	60,1	83,5	55,3	47,5	89,8	79,9	61,8	78,5	53,6	50,3	34,8	17,6
1	36,5	38,9	26,7	28,4	75,1	39,6	29,9	49	58,5	46,4	48,8	33,4	28,5	35,5	29,3

It can be observed that the resistivity strongly depends on the position where the measurement was taken, certainly due to the possibility of leakage of de-icing salt solution from the joints.

Appendix B
In-service
Infrared Thermography

1 Details of Technique

1.1 Principle of Application

Infrared thermography measures the surface temperature of the bridge under investigation. The surface temperature will depend on a number of factors, some of these factors will be dependent on the condition of structure directly behind the surface. e.g. if there was a void behind the surface, this would alter the surface temperature, by making that part of the surface heat up and cool down at a different rate to areas with out a void. Different defects within a structure can create thermal effect on the surface, e.g. voids, water and large areas of metal. The deeper the defect is the greater time the needed to monitor the surface of the structure.

1.2 Accuracy

The accuracy will depend on the type and accuracy of infrared camera used, in the survey. The accuracy will also depend on the distance from the surface the survey was carried out at. Greater detail and depth of detail can be obtained by recording of a long period of time. The size of defect identifiable will vary depending on the type of camera, the atmospheric conditions and the distance from the structure.

1.3 Applications

There is wide variety of applications for this technique, from monitoring strains in a steel beam through to global assessments of timber, masonry or concrete bridges. There are different types of camera passive and active with different levels of sensitivity, however active infrared cameras need to structure to be artificially heated.

1.4 Advantages

Using infrared thermography there is no need to come into contact with the surface. So an inspection of the structure can be under taken from a distance, in some case without the need for traffic management.

1.5 Limitations

Adverse environmental conditions (temperature – humidity) can influence the results from the technique. So an experience user is required to determine if the conditions are suitable for a survey. Some infrared camera requires liquid nitrogen to cool the camera.

1.6 Equipment and procedure

There is a large range of producers for infrared cameras. There are also a number of research cameras built by research institutions.

2. First Application

2.1 Description of application (when and how to use)
The technique can be used for monitoring the underside of a bridge deck for delaminations. The recording can be made at regular intervals through out the life span of the bridge and thus the rate of delamination growth can be determined.

2.2 Accuracy

See 1.2

2.3 Advantages

The camera can be placed in the side of the road with no need for traffic management. Lengthy time periods can be recorded and thus greater detailed obtained. An overview of the entire bridge deck can be obtained, locating areas of delamination, rather than locations results (from tap testing).

2.4 Standards/specifications

American specifications (ASTM D3398)

3. Second Application

3.1 Description of application

Assessment of welds. As a bridge moves the welds will flex and bend and if there is a weakness either in the welds or the surrounding metals, this will cause a temperature anomaly. If the locations of these were recorded over a period of time an understanding of how the deterioration of the weld is occurring.

4. Third Application

4.1 Description of application

Infrared thermography can be used to identify areas of delamination on the road surface over a bridge bridge. Corrosion of embeded steel reinforcement within a bridge deck is the main cause of deck delamination. As reinforcement corrodes it expands and creates a subsurface fracture within the concrete. When this delamination occurs in a bridge section, a disruption in thermal conduction properties of the material occurs at that local site. Bridge deck delamination can be detected during the daytime hours as a result of the natural thermal transition within the structure. Delaminations within the concrete interrupt the flow of thermal energy in the inner deck core and consequently those areas will show a different surface temperature than the surrounding solid deck area. This method of assess the delamination of the bridge will enable several surveys of the bridge to be compared as the technique involves looking at the difference in temperature rather than the absolute temperatures

4.2 Accuracy

Depends on the environmental conditions, distance the camera is away from the pavement surface, and the speed of survey.

4.3 Advantages

This technique can be used rapidly to assess many bridges in 1 day.

4.4 Limitations

The size of delamination needs to be large enough to cause a surface thermal change, and the camera needs to be sensitive enough to identify this change.

4.5 Interpretation

Basic image processing is needed for this application.

5. Sources of Further Information

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Appendix B
In-service
Magnetic flux leakage (MFL)

1. Details of Technique

1.1 Principle of Application

This technique is applicable only for ferromagnetic materials. A large magnetic field is applied to the object under question, as the magnetic moves along the object the magnetic field strength is measured at a number of points, any discontinuities (voids within the object) will be identified by a change in the recorded magnetic field. The system consists of two strong permanent magnets and a set of Hall-effect sensors. This technique requires a high degree of operator expertise to ensure that the magnetic fields are aligned in the correct direction in order to detect the defect. Flaws oriented perpendicular to the induced magnetic field, are only reliably detectable. Hence the challenge is to induce magnetic field lines in a given work piece so that they are most likely to be perpendicular to the flaw orientation. Therefore, prior knowledge on flaw orientation and /or introduction of magnetic fields in several directions are / is essential.

1.2 Accuracy

Various tests have been carried out to determine the accuracy of this method, it depends on the equipment and application.

1.3 Applications

There are a number of different applications for this method, ranging from identifying breaks in the cable of cable stayed bridges, though to locating thinning of metal plates on box girders, including the assessment of post tensioned tendons

1.4 Advantages

MFL non-invasive technique which determines the condition of a metal cable, or surface by just monitoring the magnetic field surrounding the cable or metal plate. When being used on a cable in a bridge it is possible for the equipment to work its way methodology up the cable without any interference form the operator.

1.5 Limitations

Depending on the type of equipment used there is a limitation on the depth of penetration that MFL can achieve, also the technology has yet to advance to enable precise measure of size of cracks in the cable or tendons to be achieved.

2. First Application

External post-tensioned tendons.

2.1 Description of application (when and how to use)

The MFL equipment (two magnets and a number of Hall-effect sensors) can roll along the length of a post-tensioned tendon on contact wheels which maintain a constant distance between the magnets and the surface of the tendon. Changes in the magnetic field in a post-tensioned tendon are normally measured in terms of the amplitude of the Hall-effect sensors output signals. The magnitude of the of the MFL signal for each sensor is proportional to the distance between the sensor and the defect (or the source of the magnetic field change)

2.2 Accuracy

This depends on the operator and the equipment used.

3. Second Application

Identification of cracks in cables on cable stayed bridges.

3.1 Description of application

The MFL equipment (two magnets and a number of Hall-effect sensors) can roll along the length of a cable on the cable stay bridge on contact wheels which maintain a constant distance between the magnets and the surface of the tendon. Changes in the magnetic field in the cable are normally measured in terms of the amplitude of the Hall-effect sensors output signals. The magnitude of the of the MFL signal for each sensor is proportional to the distance between the sensor and the defect (or the source of the magnetic field change)

4. Third Application

Identification of poor welds, thinning of metal plates or other defects in metal plates

4.1 Description of application (when to use)
MFL / magnetic particle inspection can be undertaken to identify these defects on metal plates by creating a magnetic field within the metal plate by introduction two magnetic on to the surface of the metal plate and by scattering iron particles or metal dye over the surface and were there is a defect there will be a clumping or grouping of the iron particles or dye.

4.2 Accuracy

The accuracy depends on the size of defect and the location of the defect as well as the geometry of the steel plate.

4.3 Applications

Longitudinal cracks at welds, thinning of the plates, pitting of the plate

4.4 Advantages

It provides a simple method for a preliminary sweep of a metal plate to identify the location of any possible defects both in the plate and in any welds.

4.5 Limitations

Depth and severity of the defects are impossible to determine

4.6 Equipment and procedure

Create an magnetic field in the metal plate or weld by using two magnetic placed within 30 cm of each other (depending on the strength of the magnets).

Appendix B
In-service
Impact echo (IE)

1. Details of Technique

1.1 Principle of Application

The impact-echo technique is a non-destructive test capability that allows accurate measurement of a member's thickness as well as detection of internal defects such as voids, honeycombing, cracks, delamination and poor quality concrete. An IE test consist of introducing a small mechanical impact on the concrete surface and measuring and recording the resulting surface displacements close to the impact point. The surface motion is due to reflections of the impact waves from the concrete member's back face and from various interfaces (or defects) inside concrete. In an IE test the recorded surface displacement data is converted into frequency values that correspond to distances from the concrete surface to respective interfaces. Therefore in addition to detecting the presence of the defect inside a concrete member, one can also determine the location of the defect

1.2 Accuracy

The accuracy depends on the location, the operator and the equipment.

1.3 Applications

The applications concern the identification of defects with a beam, column or slab.

1.4 Advantages

The results received when calibrated can be directly transferred to distance and thus giving the depth of the defect.

The technique can differentiate between different types of defect.

1.5 Limitations

Detailed geometry of the structure in question must be known for calibration. It can only be used on structures, which the technique has been tested on in the past. It cannot be used on structures over a certain depth.

2. Application

Identification of voids within an internal post-tensioned duct.

2.1 Description of application (when and how to use)

Traditionally it can be used to assess the condition of metal post tensioned ducts. It is used to identify the location and magnitude of voids.

2.2 Accuracy

Some initial studies showed that IE can identify voids of a size greater than half of the volume of the metal duct.

Appendix B
In service
Acoustic emission (AE)

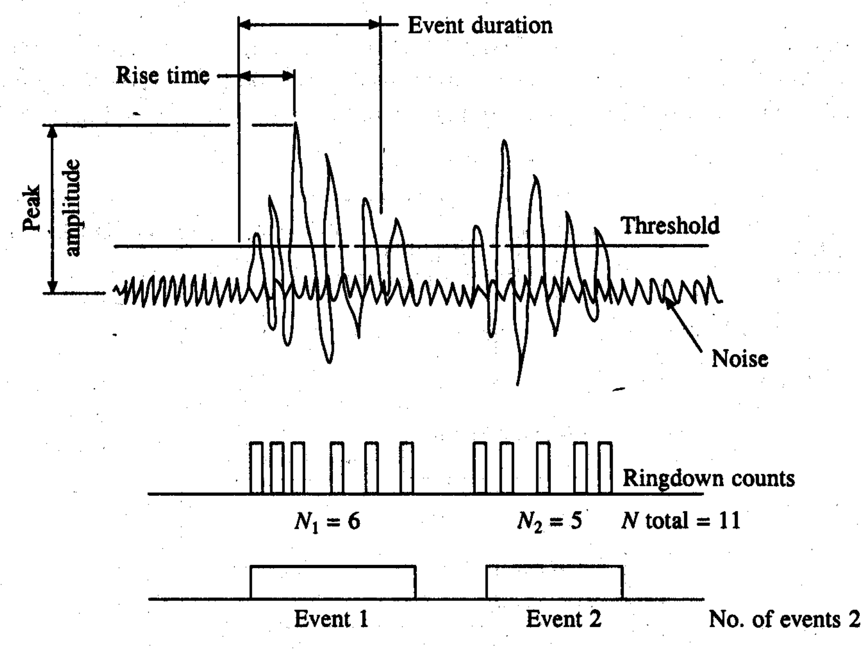
1. Details of Technique

1.1 Principle of Application

Acoustic emission inspection defects and analyses minute AE signals generated by discontinuities in material under a stimulus such as stress, temperature etc. Proper analysis of these signals can provide information concerning the detection and location of discontinuities and the structural integrity.

Another important feature of AE is its irreversibility. If a material is loaded to a given stress level and then unloaded, usually no emissions will be observed upon immediate reloading until the previous load has been exceeded. This is known as the Kaiser effect and is due to the fact that AE is closely related to plastic deformation and fracture. This irreversibity of AE has important practical implications because it can used in the detection of sub-critical growth of flaws, such as fatigue crack growth, stress corrosion cracking, hydrogen embrittlement, etc.

There are many different feature of the signal that can be identified to finger print the signal and identify what type of event caused the sound. The figure below shows the different aspects of the signal that are characterised.



Normally an AE system will either, be attached permanently to a structure and will be left to constantly monitor critical parts of the structure, or be installed on a structure to identify the heath of the structure or parts of the structure at any point in time, or as part of an on going assessment program.

1.2 Accuracy

AE is able to identify and locate any event which is greater than the threshold and is received by more than 2 sensors (for location).

AE inspection is extremely sensitive compared with the other more familiar NDT methods. The minimum detectable crack size for ultrasonic testing, radiography testing and eddy current testing methods is about 0.50mm (in metals), if ideal conditions are net for each method.

Whereas AE can detect crack growth in metals of the order of 25 microns. This corresponds to microcrack growth of the order of less than 10μm

1.3 Applications

There are many different types of application for this technique, for instant, identifying cracked shear studs on a composite bridge deck, locating concrete cracking on a concrete bridge, identifying areas of metal fatigue etc. There are different sensors that can be used on concrete and steel bridges as they emit different frequency of acoustic emissions. This means that it is the same technique can be used on different materials but with different signal processing.

1.4 Advantages

An AE system can remain on a structure and constantly monitor the structure for critical component failures e.g. post –tensioned wire breaks. Or an AE system can be used to taker snapshots of the health of a bridge under ambient load or forced loading

1.5 Limitations

AE systems tend to be quite expensive, the data analysis is not always trivial, requiring a skilled operator and lots of computer memory and disk space. The emissions depend on the load configuration and on the material and are affected by inelastic attenuation and background noise. Although AE systems can locate defects and cracks they cannot determine the absolute size only the latest crack growth increment

1.6 Equipment and procedure (including details of suppliers/web sites)

There are two main suppliers of AE systems in the USA and UK, Physical Acoustics (www.pacuk.co.uk/) and Soundprint (http://www.soundprint.com/index_0.htm).

A standardised procedure for civil engineering structures does not exist yet.

2. First Application

2.1 Description of application

Wire break in post-tensioned beams. This is a common application of this technique as when the wire snap as they are under tension they will let off a unique acoustic emission, different to any that would normally occur in or around a bridge. This technique can identify breaks in internal and external post-tensioned ducts.

2.3 Accuracy

Due to the complex nature of the structure in question it is very hard to determine the sensitivity of the technique however manufacturers and consultancies claim a very high accuracy for this technique based on past experience and the fact that the AE generated by wire breaks is very unique. As wire breaks generate a very high energy, high rise time, and short duration acoustic emission.

2.4 Advantages

A whole bridge can be monitored with relatively few sensors (1 or 2 sensors per meter square). The system can be set up with some predetermined threshold filters which only register wire breaks and thus every time a wire breaks the system can automatically notify the bridge manager of the event. If the event is located by more than 2 sensors it is then possible to locate the position of the wire break

2.5 Equipment and procedure

A number of sensors are placed on the underside of the bridge deck and the bridge is monitored under the normal traffic conditions.

2.6 Interpretation

The software automates the interpretation at the moment, where it is just identifying signals that are similar to wire break events.

3. Second Application

3.1 Description of application

The identification of broken shear studs in a composite bridge deck. This is an important application as this technique can identify the location and occurrence of broken shear studs in the bridge deck, which can weaken the composite action between the concrete deck and the metal beams. The sensors are placed on the metal beams and then any events are recorded and located. It is possible to identify the shear studs in various forms of decay, at early fatigue crack and failed studs. In practise a bridge would only needed to be monitored over a relatively short period of time to identify the shear or cracked studs.

3.2 Accuracy

Research and testing has shown that it is possible to identify early stage of fatigue cracking in the shear studs and failed studs

3.3 Advantages

The bridge can be monitored either continually or at regular intervals to identify shear stud failure. This is one of the few techniques to identify this failure mechanism.

4. Third Application

4.1 Description of application

Locating cracks in concrete and masonry arch bridges. By attaching sensors to the underside of the bridge (either concrete or masonry arch) it is possible to locate cracking events under either forced or ambient loading. This can be inputted into a strength assessment model to identify areas of active cracking for the bridge

4.2 Accuracy
The accuracy of this application depends on the spacing of the sensors as on masonry the AE signal gets dispersed by the mortar joints

4.3 Advantages

Under forced loading it is possible to identify the previous maximum load the bridge has been subjected to, using the Kasier effect.

5. Sources of Further Information

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Appendix B
In service
Ultrasonic testing (UT)

1. Details of Technique

1.1 Principle of Application

Ultrasonic testing is a versatile NDT method, which is applicable to most materials, metallic or non-metallic. By this method, surface and internal discontinuities such as laps, seams, voids, cracks, lack of bond, etc. can be accurately evaluated form one side. Ultrasonic testing utilises high frequency acoustic waves generated by piezoelectric transducers. Frequencies form 10 to 10 MHz are typically used, although lower or higher ranges are sometimes required for certain applications. The resultant acoustic wavelength in the test material (depend on the ultrasonic wave velocity) are of the order of one to ten millimetres. A highly directional sound beam is transmitted to the test piece through a suitable couplant, usually grease or oil like material. While various types of instrumentation and display modes are feasible, the most widely employed is the pulse-echo technique.

Since acoustic waves propagate effectively through most structural materials, but are dissipated or reflected by in homogeneities or discontinuities, measurement of the transmitted and reflected energies may be related to the integrity, which is a function of the material in homogeneity an defect parameters. Ultrasonic test method provided quantitative information regarding thickness of the component, depth of an indicated discontinuity, size of the discontinuity etc.

1.2 Accuracy

The smallest defect that this technique will be able to find will be about half of the wavelength in the direction of travel for the wave. The wavelength is dependant on the frequency used.

1.3 Applications

Typical applications of ultrasonic inspection are:

- Surface breaking and hidden cracks in any orientation
- Inter-granular cracks
- Laps
- Laminations / delamination
- Volumetric defects such as slag inclusions, voids, etc.
- Porosity
- Wall thickness measurements
- Creep
- Hydrogen embrittlement
- Honeycombing
- Location of snaps in post tensioned ducts. (internal and external)

1.4 Equipment and procedure

Most ultrasonic inspection instruments detect flaws by monitoring one or more of the following variables:

- Reflection of sound energy
- Transit of sound wave
- Attenuation of sound energy

Based on the variable that is being used for knowing the healthiness of the material, a specific type of instrumentation is selected. Although the electronic equipment used by different manufacturers for ultrasonic inspection can vary greatly in detail, all general purpose equipment consist of a power supply, a pulser circuit, a search unit, a receiver-amplifier circuit, an oscilloscope and an electric clock.

Multichannel equipments are used for testing components by a number of probes simultaneously. Suitable manipulators are required to enable such inspection. There are various other types of advanced ultrasonic instruments; however these instruments have not gained popularity due to the advanced operator knowledge needed and the cost and sophistication of the system.

2. First Application

2.1 Description of application

In the assessment of shear studs. After the location of the broken or partially cracked shear studs are assessed using acoustic emission. An ultrasonic scan of the stud form the under side of the metal beam will confirm or reject the diagnose of the AE.

2.2 Accuracy

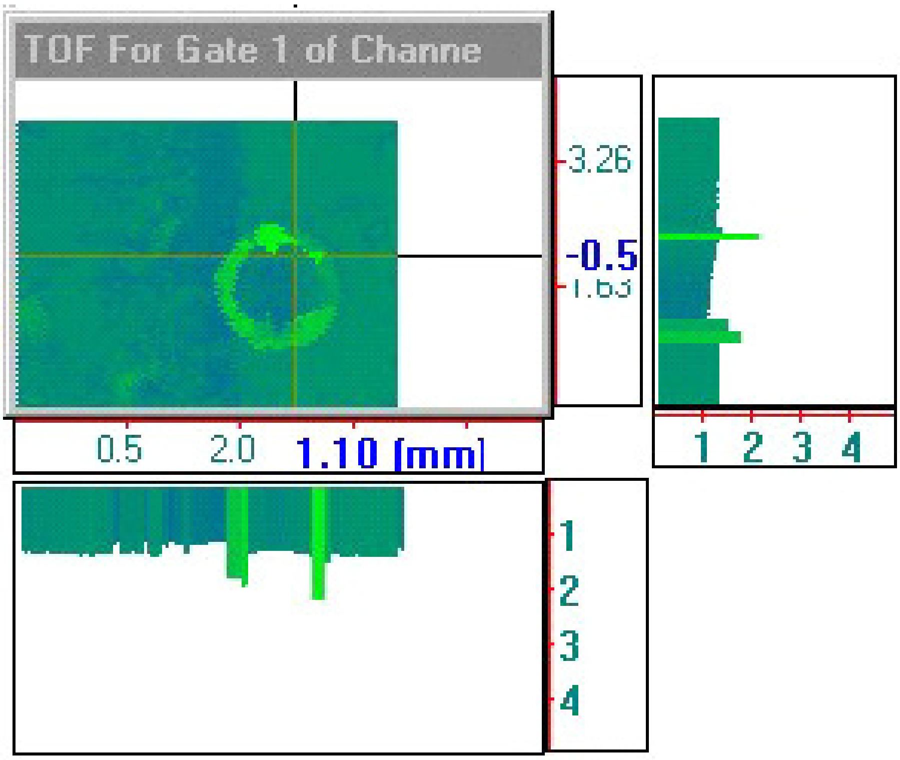
The accuracy of this method depends on the wavelength of the signal used. For identification of cracks the crack width needs to be about half of the wavelength.

2.3 Applications

This technique can be used to validate the AE results in all types of composite bridge deck construction.

2.4 Advantages

It can be used to confirm the findings from an AE investigation. The technique will provide an image of the cracked or intact stud so it can be compared at regular intervals to see if the crack is growing and by how much. The figure below shows an ultrasonic scan of a cracked shear stud.



2.5 Limitations

The main limitations are that the technique required contact with the underside of the bridge deck. This operational access to the bridge deck is expensive and the technique is very slow so AE can be used to maximising its use by specifying were the technique should be used.

3. Second Application

3.1 Description of application

Long range crack detection in welded girder-diaphragm connections using Lamb Waves.

Guided ultrasonic lamb waves are used to evaluate bridges containing fatigue cracks in the diaphragm connections. The Lamb waves are introduced into the girder and it travels along the girder and is reflected by any discontinuity such as cracks. The reflected signal is received and analysed in a similar way to that of a radar signal.

3.2 Accuracy

The size of crack possible to be detected depends on weather the crack is in the compression or tension zone (i.e. if the crack is currently open or not)

3.3 Applications

It is possible to assess a girder by placing the guided wave transducer and receiver at one position of the bridge. A pulse will be induced into the girder and the reflected signal received and analysed.

3.4 Advantages

The main advantage is that there is no need for access to the whole of the girder rather just at one place and the whole girder can be assessed form that point.

3.5 Limitations

It is very hard to determine the exact position of the fatigue cracks if they are very close to the weld, cracks which are in the compression zone at the time of testing may be easily identifiable..

4. Sources of Further Information

Woodward, C. and Stone B., 1998, Long range crack detection in the weld girder – diaphragm connection using Lamb waves, Final report for New Mexico State Highway and Transportation Deptartment

Appendix B
In service
Ground penetrating radar (GPR)

1. Details of Technique

Over the past decade there has been an increasing usage of GPR to investigate civil engineering problems and in particular, concrete structures.

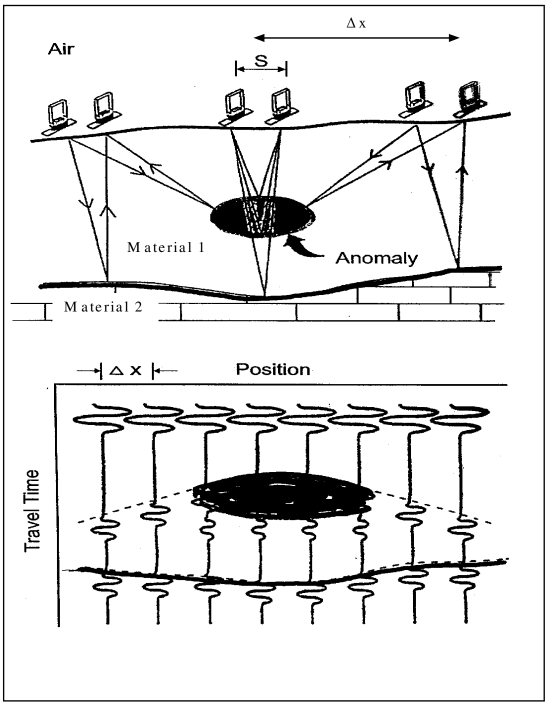
1.1 Principle of Application

Over the past decade there has been an increasing usage of GPR to investigate civil engineering problems and in particular, concrete structures.

1.2 Accuracy

Electromagnetic waves, typically in the frequency range 50 MHz to 2 GHz, will propagate through solids, with the speed and attenuation of the signal influenced by the electrical properties of the solid materials. The dominant physical properties are the electrical permittivity, which determines the signal attenuation. Reflections and refractions of the radar wave will occur at interfaces between interpreted to provide an evaluation of the properties and geometry of the sub-surface features. See the below figure. If surveys are undertaken at regular time intervals it should be possible to map the deterioration of the structure. Or if the condition is unknown a GPR survey will reveal certain construction features, which can be inputted into a assessment model. (this may be difficult to define)

If the properties of materials are known precisely it may be possible to make depth estimates to within about ± 5 mm (depending on the frequency used), however in practise uncertainties and material variability are likely to increase this error range.



1.3 Applications

Typical applications of radar are

- Determination of major construction features
- Assessment of element thickness
- Locating reinforcing bars
- Locating moisture
- Locating voids / honeycombing / cracking
- Locating high levels of chlorides
- Determine the size of reinforcing bars
- Determine the size of voids
- Estimating chloride concentrations

1.4 Advantages

GPR is a proven technique on a number of different applications, including the use on concrete, it is a mature technology. The software analysis of this technique has also become very sophisticated over the last few years and the data manipulation has improved.

1.5 Limitations

Due to the difficulties in interpreting radar results, surveys are normally conducted by testing specialists who rely on practical experience, have a knowledge of the fundamental principles involved and have a sense of realism concerning the likely limitations in a given practical situation. It has been shown that details such as voids can be difficult to identify and determine if located very deep or beneath a layer of closely spaced reinforcement.. Contact is needed to the surface over were a survey needs to be undertaken, so a closure of the bridge may need to be undertaken.

1.6 Equipment and procedure

There are many different companies making GPR equipment

2. First Application

2.1 Description of application (when and how to use)

To survey bridge decks from a moving vehicle to detect corrosion induced delamination of the reinforced concrete slab. An array of antennae could be towed behind a car over the bridge deck.

2.2 Accuracy

The accuracy depends on the frequency used, a higher frequency will give better resolution but will not penetrate that far, while a lower frequency will give greater penetration but at a lower resolution.

Appendix B
In service
Vibration measurement

1. Details of Technique

1.1 Principle of Application

This technique can be used on whole structures or particular parts of a structure of special interest. Bridges like many other structures have an individually developed vibration behaviour which may be addressed as a 'vibration signature'. This dynamic behaviour typical for a structure can be registered by appropriate measurements and be used for the assessment of the condition of the load-bearing structure and the determination of damages after respective evaluations. This structural response can be well described by the modal parameters eigenfrequencies, mode shapes as well as the respective damping values.

Accelerometers are attached to either parts of a bridge or globally and the bridge or structural element is either forced to vibrate or measured under ambient conditions. The accelerations are then measured and from them the modal shapes and natural frequencies of the element or whole bridge can be determined.

If the bridge is monitored over time and there is a shift in the natural frequencies or modal shapes this is indicative of a structural change (e.g. damage).

If it is possible to determine the initial condition of a bridge, if it was not possible to record the vibration when new, using finite element (FE) models.

1.2 Applications

This technique has been generally used on large bridges as a method of continuous health monitoring of the bridge, as any defect e.g. snap in cables of a cable stayed bridge or deterioration of a joint or abutment will alter the global natural frequencies. Generally the types of bridge that have been monitored in this way have been large cable stayed bridges, but also post-tensioned bridges have been monitored.

1.3 Advantages

This technique is capable of monitoring the bridge continuously.

1.4 Limitations

- The data processing of the eigenfrequencies are very difficult.
- If the bridge is not monitored from new it is impossible to determine what damage has already occurred.

When there is a change in eigenfrequencies it is impossible with out using complicated FE models to determine where the damage occurred or even how serve is the damage.

Appendix B
In-service
Long Tern Corrosion Behaviour
Sensors: 6 Optical Fibre Strain Gauges

Strain gauges can be either embedded in the concrete/grout for installation during construction or can be mounted on the structure surface for retrofitting purposes.

1. Details of the Technique

1.1 Principle of Application

These strain gauges can measure strain at discrete lengths along the length of a single sensor whose length can be as long as 100m and as such they have a distinct advantage over conventional strain gauges. The characteristics of the light passing down the fibre are altered when the fibre is subjected to stress. Bending, stretching, or compressing the fibre changes the geometry of the fibre and this effects the transmission of the light signal. For example bending results in a loss of transmitted light intensity and stretching of the fibre alters the frequency of transmitted light waves.

An optical fibre sensor consists of a glass fibre, typically of 5µm diameter that is covered with a relatively thick plastic coating (125µm) and jacket to protect it from both physical damage and chemical attack by the alkalis in concrete. The plastic coating is designed with a slightly lower refractive index than the glass fibre to ensure that the light passing down the fibre is totally internally reflected on contact with the fibre walls and is not therefore lost into the surrounding coating. The bond between glass fibre and the plastic coating is strong enough to transmit strains from the structure to the fibre. Fibre optic sensors have in general proved to be remarkably robust when embedded in concrete structures.

1.2 Accuracy

Optical Fibre Strain Gauges are comparatively sensitive being able to measure strains as small as 0.1 microstrain compared with values of greater than one microstrain for conventional strain gauges.

1.3 Applications

The application concerns the measurement of the strains generated in reinforced concrete structures arising from the long-term corrosion behaviour in corrosive environments which produces a reduction of reinforcement section and loss of steel-concrete bond.

The sensors can be embedded in the concrete during construction or surface mounted in service.

1.4 Advantages

The main advantages are:

- Each sensor can be up to 100m long with low signal loss and hence can monitor strains over a large area.

- Immunity of sensor from corrosion
- Ease of installation
- Not subject to electromagnetic interference
- Robust
- Can be embedded or surface mounted
- High sensitivity
- Long life and stability
- Can monitor strains, cracks and displacements

These advantages overcome many of the limitations of conventional strain gauges.

1.5 Limitations

The high cost of equipment and the expert personnel needed to install and maintain the equipment and interpret the data.

Some types of sensor need to be calibrated or compensated for ambient temperature changes. This can be achieved with a thermocouple or with a reference fibre that is not subjected to strain.

1.6 Equipment

1.6.1 Sensors

There are four main types of fibre optic sensor used in civil engineering structures

- Interferometric   Fabry-Perot
- Interferometric   Michelson (SOFO)
- Spectrometric   Bragg Grating
- Micro-bending

Interferometric sensors measure changes in the light at the end of a single fibre. Spectrometric sensors measure changes in light wave frequency over a short section (grating) of the fibre and many gratings are multiplexed on a single fibre. Micro-bending sensors measure displacements at locations along the full length of the fibre.

The gauge lengths of the Fabry-Perot and Bragg Gratings are short (~ 20mm) although the Bragg gratings can be multiplexed with up to 30 sensors incorporated in one fibre. The gauge length of SOFO sensors is about 200mm and for micro-bending sensors it can be over 100m.

The resolution of interferometric sensors is about 2 microns, Bragg gratings about 1 micron, and microbending sensors about 30-100 microns. The SOFO sensors have been the most widely used type for bridges. Microbending sensors are well suited to short term dynamic monitoring.

1.6.2 Monitoring Equipment

Fibre optic sensors are normally sold as complete systems (sensor + monitoring equipment) because of the expertise needed for installation, operation and data interpretation. Manufacturers include:

- Smart Fibres, UK
- Smartec, Switzerland
- FISO Technologies, Canada

Fibre optic sensors and monitoring equipment are relatively costly.

2. Application

2.1 Description of Application

The application of Fibre Optic Sensors is suitable for structures situated in corrosive environments. The technology can use either sensors embedded in concrete/grout during construction or sensors surface mounted on to the structure during service life. The number and positioning of embedded sensors must be decided at the design stage of the structure.

2.2 Interpretation

The measurements involve changes in light intensity and frequency. How these changes relate to strains and displacements is complex thus skilled and experienced personnel are needed for the interpretation of fibre optic data.

2.3 Applications

The SOFO fibre optic system has been used in more than 50 civil engineering structures such as bridges, tunnels, piles, anchored walls and nuclear power plants.

3. Sources of Further Information

Ansari, F (1997). State-of-the-art in the applications of fibre optic sensors to cementitious composites. Cement and Concrete Composites, Vol. 19, pp. 3-19.

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Lau, K-T. (2003). Fibre-optic sensors and smart composites for concrete applications. Magazine Concrete Res., Vol. 55, pp. 19-34.

Leung, C.K.Y. (2001). Fiber optic sensors in concrete: the future? NDT & E International, Vol. 34, pp.85-04.

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APPENDIX: C

Novel Methods Under Development

Novel Methods for Monitoring Reinforcement Corrosion

A number of methods are currently under development. They have not yet been used in the field but they have features that make them potentially attractive. Some of the methods are adaptations of similar methods used in other fields. They all at present pose difficulties of data interpretation and doubtless further research will be targeted at these difficulties. This document only provides brief notes on each method sufficient to raise the awareness of practitioners.

Electrical Time Domain Reflectometry (ETDR)

This method has some similarity to optical time domain reflectometry and its anticipated use is to determine loss in cross section of reinforcement and prestressing wires in concrete and steel tendons in grouted ducts due to corrosion. The method is an adaptation of the technique used by electrical engineers to locate faults in transmission lines. It involves passing an electrical pulse down the steel wire/tendon; any discontinuity will result in a reflection from which it is possible to determine its location and nature. The sensor is an insulated copper wire that is installed parallel to the tendon under examination. The sensor wire can be mounted either inside or outside the duct thereby allowing the possibility of retrofitting.

Evaluation trials have been disappointing. The conclusions from one trial was that "the recorded sigals do not contain information regarding the condition of the tendon but are artefacts of the measurement procedure. Thus RIMT can definitely not be used as a diagnostic technique for grouted tendons" (Matt, 2001).

Matt P (2001). Non-destructive evaluation and monitoring of post-tensioning tendons. Durability of post-tensioning tendons. FIB Workshop 15-16 November 2001.

Harmonic Sensors

These sensors are claimed to measure temperature, stress and corrosion in concrete. The principle of the sensor is based on changes in the harmonic signature of magnetically soft, high permeability materials, such as steel, subject to corrosion. The sensor can measure changes over extended distances that are relevant to tendons in ducts where corrosion occurs randomly over their length.

Electrochemical Impedance Spectroscopy (EIS)

This method measures the polarisation of a sensor probe to generate the linear polarisation resistance and corrosion rate. The equipment and interpretation are more complex than for the LPR method although more information is produced such as the dielectric properties of the concrete and the passive film on the steel. The method has been used to study coatings and interfaces particularly the bond between carbon fibre reinforced polymer (CFRP) and concrete. The EIS sensors are long wires and measure the response over a long length thus avoiding the necessity for multiple point sensors.

Hydrogen Monitoring

The principle of this method is detection of hydrogen produced at the cathode of the corrosion cell by the reduction of hydrogen ions. This cathode reaction only occurs to a very limited extent in alkaline media such as concrete hence this technique would not be expected to be of much interest. Steel tendons in post tensioning ducts, however, are not always completely covered with grout, sometimes resulting in stress corrosion cracking by hydrogen embrittlement as a consequence of hydrogen evolution at the cathode. Sensitive hydrogen monitors are capable of detecting small concentrations of hydrogen in a confined space such as a post-tensioning duct. This detection of hydrogen would suggest non-alkaline conditions and a risk of hydrogen embrittlement of highly stressed steel although it is difficult to understand how this could be quantified.

Novel Methods for Measuring Structural Changes

These methods are still under development and so cannot at present be applied to structures. They have significant problems that need to be overcome before they can be usefully applied particularly about the interpretation of the measurements. In this document short notes are provided about these methods to raise the awareness of practitioners.

Shearography

This represents a group of non-destructive optical methods that are proposed for whole field inspections of structures using non-contact methods. The techniques include holography, digital shearography and electronic speckle pattern interferometry (ESPI)

Defective structures often experience strain concentrations in the region of the defect when loaded, leading to anomalies in the distribution of surface strain. A comparison of the surface strain distributions before and after loading, using these techniques, can help in defect location.

Shearography has been used successfully in the aerospace and automotive industries and it is anticipated that it could be effective for the detection of cracks, voids and corrosion in concrete structures.

Magnetorestrictive Sensors

The principle of this method is that magnetic materials change their shape in a changing magnetic field. When steel is lost from a reinforcing wire or bar due to corrosion there is a change in its magnetic field and the resulting change is shape produces a wave that is transmitted along the wire to the sensor sited at its end.

This is a non-contact, non-destructive method that could be used to monitor corrosion damage on long steel strands. The method currently shows promise when applied to wires in air but attenuation losses for wires in concrete are high.

Conductive Paint

The principle of this method is that cracks forming in conductive paint films produce large changes in the electrical resistance of the film that can be detected. The method could be used for detecting cracks in concrete structures such as tunnel linings. The method involves painting strips of a graphite based conductive paint along the surface of the structure.

TRIP Sensors

Transformation induced plasticity (TRIP) steel sensors use a special steel that under stress experience a permanent change in crystal structure causing a change from non-magnetic to magnetic properties in proportion to the peak strain. This method could be used to non-destructively monitor the maximum load experienced by a bridge and to detect overloading.