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Intelligent monitoring of concrete structures

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Summary

Management of concrete structures requires an understanding of the deterioration processes involved and the rate at which they proceed. Intelligent monitoring is automated monitoring which explicitly provides information on current condition and deterioration rates to assist in predicting the remaining life of a component or structure. Surface mounted or embedded sensors may be used to monitor various aspects of structural condition, reinforcement corrosion, and the environment in and around a concrete structure.

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Foreword

In October 2004 the DTI awarded a 2 ½ year contract to a partnership between CIRIA and Imperial College to investigate the existing technology for automated monitoring of the deterioration of concrete structures and the models available to use the data obtained for the prediction of remaining service life.

The work was commissioned by the National Measurement System Directorate (NMSD) under the Materials Metrology Programme and was designed to sign-post industrial needs, opportunities and possibilities to guide industry and the DTI for future work in this technology area. The Industry Advisory Group formed by CIRIA to guide and inform the work was an important factor in the development of the project.

Reports on these two topics (monitoring and modelling) were submitted to the DTI in June 2007, together with a roadmap exploring the way forward and these reports inform and underpin this guide, and they are provided as a CD with the guide.

The subject area has proved to be extensive, young and dynamic with practitioners active throughout the world. The information gathered and the understanding gained is considerable. Some key points from the work are:

- there are many reasons to monitor structures including to compare the actual behaviour with that anticipated during design, to determine the rate of deterioration, to optimise the timing of maintenance and to warn of an impending failure
- automated monitoring offers potential benefits in relation to on-site testing, including reducing the need for access, identifying problems earlier and isolating climatic effects
- sensors and monitoring equipment are available to allow many important aspects of the behaviour of concrete structures to be automatically monitored including aspects of structural change (eg deflection, vibration, displacement, concrete and rebar strain and pre-stressing wire breaks), reinforcement corrosion (eg half cell potential, polarisation resistance and concrete resistivity), concrete temperature and moisture content
- a study of the case studies provided demonstrates that intelligent monitoring is a worldwide issue and the large number of providers of instrumentation listed demonstrates the depth and breadth of effort being devoted to it. There are examples of intelligent monitoring being successfully used to manage structures
- there are many potential obstacles to the adoption of monitoring. These include concerns over the accuracy, stability and durability of some types of sensor, the fact that very few service life models are able to utilise monitoring data and the difficulty of sustaining owner management systems over long periods. This guide makes the difficulties clear and provides access to information in support of decision-making
- with developments in wireless communications and sensor technologies and a better understanding by industry of what can be done, there is no doubt that future management of our built environment will increasingly benefit from the use of intelligent monitoring.

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Intelligent monitoring CD

Attached to the inside back cover of this book you will find a CD-ROM containing three DTI reports:

1 ***Automated monitoring of the deterioration of concrete structures.***
2 ***Service life prediction of concrete structures based on automated monitoring.***
3 ***A roadmap for the development of intelligent monitoring of concrete structures.***

1 Introduction

1.1 BACKGROUND

Most of the developed world's infrastructure is built in concrete. The majority is required to remain in service for at least 50 years and structures such as major bridges, dams, heritage buildings and nuclear storage facilities are expected to have lives of over 100 years. In some cases owners expect their structures to continue in use almost indefinitely. For example, underground railways in city centres generally remain in use for as long as they can be kept in a safe condition, regardless of cost. With appropriate design, selection of materials and construction practice it is possible to produce concrete structures that will be adequately durable in most exposure environments. However there is a legacy of structures where deterioration is causing problems leading to excessive maintenance expenditure and in some cases premature replacement.

Concrete structures do deteriorate and the complex chemistry of cement, the use of steel reinforcement and the variety of exposure environments result in many often interacting degradation processes. For most structures deterioration is so slow that no early intervention is needed. However, eventually deterioration becomes more rapid and repair or replacement is required. This is costly in terms of the materials and labour used, the disruption to users and other social costs. Unexpected failures can have particularly severe financial, environmental and safety implications and may leave companies liable to prosecution and compensation claims.

As deterioration progresses, it becomes increasingly expensive to rectify. So it is important to identify deterioration early, determine its structural significance, and to monitor the structure so that a timely intervention is possible avoiding more serious problems. Often early protective and remedial action, if monitored, can substantially prolong the useful life of a structure. Monitoring is now primarily based on visual inspection. Risk assessment (often informal) is based mainly upon experience elsewhere, informed by such inspection. Sampling, testing and in situ monitoring are rare until problems become serious. They are usually driven by obvious concerns and not by developing problems that have not yet become visually evident. The limitations of this approach are particularly worrying when considering foundations and other inaccessible details where local severe deterioration can develop.

It is envisaged society will insist that the condition and risks for all significant structures are certified. This is likely to be demanded when some major high-profile structures have failed due to unseen deterioration. Those responsible for certification will require much more information to base their recommendations upon, such as the changing condition and strength of the structure and its likely performance in the future. Information on the changing behaviour of the structure will ideally come from sensors mounted on the structure providing real time condition information. Automated monitoring of this kind is already in place on a few structures, with measurements being taken via surface-mounted or embedded sensors and the data being transmitted to a remote office. To predict performance in the future from this data and to be able to estimate the remaining life of a structure requires a life prediction model.

Intelligent monitoring is automated monitoring which explicitly provides information on current condition and assists in predicting the remaining life of a component or structure

Currently there is active worldwide research in this area. This is aimed at developing and applying a wide range of sensors and at building models, which enable predictions to be made about future performance. In 2004 the National Measurement System Directorate of the Department of Trade and Industry (DTI) commissioned CIRIA and Imperial College to investigate the current state-of-art in the area of concrete construction. This work comprised a 30-month contract to investigate both sensors and how they are used and the available life prediction models and to prepare a state-of-the-art report including a road map for the future development of the technology in this area. The work was guided by an Industry Advisory Group (IAG) comprising of representatives of organisations responsible for owning and managing structures and those active in developing and applying the technology, and their names are listed on page iv. The three reports prepared for the DTI are enclosed with this guide on CD-Rom and should be referred to for further detailed information as necessary.

This guide is based upon the DTI project. It is designed to provide an introduction on the subject of intelligent monitoring and to assist users to access the wealth of information in the DTI reports. Users should be aware that intelligent monitoring is at an early stage of development and that its use will require specialist expertise both in initiating and managing the process and in carrying out the work. Engineers should actively look for and apply further developments in monitoring, which can be expected as outlined in the road map for the future development of this field.

1.2 HOW TO USE THIS GUIDE

This guide is written for all of those with an interest in monitoring including asset owners, consulting engineers, specialist contractors, suppliers and researchers.

Users of this guide may access information in the sections as follows:

1 The role of intelligent monitoring in the management of structures	Intelligent monitoring is one aspect of the management of structures. This section will assist in understanding how it fits into the wider picture.
2 Automated monitoring	This section explains the state-of-art of automated monitoring in 2007 with emphasis on techniques with a proven track record.
3 Prediction of remaining life based on monitoring data	Ideally the outputs from monitoring are fed into a model to provide guidance on the remaining life of a structure. This section describes the models available and how they may be used with monitoring data, exploring their attractions and limitations.
4 Case studies	An overview of the case studies in DTI Report 2 Appendix A2 to illustrate what has already been done.
5 Looking to the future	Here the guide explains what the future may hold and identifies areas meriting further research.

1.3 THE DTI REPORTS

This CIRIA guide is based on three reports produced during a DTI funded project, Intelligent monitoring of the deterioration of concrete structures. These reports are included on the CD attached to this CIRIA guide. They provide a greater level of detail than appropriate to include in this guide and are frequently referred to throughout the guide. If a discrepancy is found between the CIRIA guide and one of the DTI reports, the CIRIA guide should be taken as the more reliable source because the CIRIA guide was finished six months after the DTI reports and was more heavily scrutinised.

DTI report 1: Automated monitoring of the deterioration of concrete structures (Davies and Buenfeld, 2007)

This report presents the state-of-the-art in automated monitoring of the deterioration of concrete structures. It focuses on what is now practical, but also refers to methods under development. Considerable detail is provided on the sensors available to monitor:

- structural change (Chapter 3)
- reinforcing steel corrosion (Chapter 4)
- concrete moisture state and temperature (Chapter 5)
- concrete chemistry (Chapter 6)
- exposure environment (Chapter 7).

These chapters are sub-divided according to what is monitored. For each of the main methods, they highlight the measurement principle, advantages (in relation to competing techniques) and limitations, the equipment used and potential application areas. Chapter 3 of this CIRIA guide is based on this report.

The appendices contain a mass of useful information:

Appendix A1 provides datasheets for the different generic types of sensor and monitoring equipment together with a list of equipment manufacturers/suppliers and their contact details.

Appendix A2 presents 32 case studies reporting on experience in applying monitoring systems to various structures.

Appendix A3 lists journals and conferences that publish papers concerned with monitoring concrete structures.

DTI Report 2: Service life prediction of concrete structures based on automated monitoring (Karimi and Buenfeld, 2007)

This report reviews a large number of models for predicting the service life of concrete structures and discusses which are the most appropriate for use with data derived from automated monitoring. Models are empirical, analytical or numerical in nature and it is this characteristic that dictates the quantity and availability of the required input parameters. An overview is presented highlighting the main differences between modelling approaches, and probabilistic techniques are presented and discussed. The vast majority of service life models presented in the literature and used by industry have been developed independently of advances made in the field of automated monitoring. In many cases the role of intelligent monitoring is restricted to providing only one or two of the input variables and in a significant number of the models reviewed intelligent monitoring cannot take any active role in the assessment process. Chapter 4 of this CIRIA guide is based on this report and focuses on the models that are most appropriately used with monitoring data.

DTI Report 3: A roadmap for the development of intelligent monitoring of concrete structures, (Buenfeld, 2007)

This report presents a roadmap for the future development of the field of intelligent monitoring of concrete structures and is primarily based on the views of the Industrial Advisory Group for the DTI Project. It summarises the current state-of-the-art, presents a vision for the future and analyses what needs to be done to realise that vision. Chapter 6 of this CIRIA guide is largely based on this report.