Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot Watt/Edinburgh)

Unit of Assessment: B15: General Engineering

Title of case study: Effective Design and Operation of Concrete Infrastructure

1. Summary of the impact (indicative maximum 100 words)

ERPE research has made major impacts on the design and operation of concrete infrastructure through design, corrosion investigation/residual life prediction and non-destructive testing (NDT). New interpretations of ground penetrating radar (GPR) data have impacted international practice through: the American Concrete Institute (ACI) document on NDT of Concrete, ACI 228.2r2013; fib Model Code 2010, ISBN:978-3-433-03061-5; a corrosion monitoring device; and "GprMax", the world's most widely used and acclaimed GPR freeware.

The financial impact of the underpinning ERPE research is estimated at £100M p.a. on infrastructure maintenance savings worldwide.

2. Underpinning research (indicative maximum 500 words)

The ERPE Concrete and NDT Group were all in post throughout the period unless stated otherwise: Professors Forde, McCarter, Usmani and Chrisp; Senior Lecturers Cairns and Giannopoulos; Lecturers Hardy and Law (to 2010); Research Fellow Starrs. In addition: PDRA's Blewett and Ezirim; and many PhDs (now employed by the industry): Diamante (2008 to Sensors & Software, Canada), Clark (now CH2MHill, Dubai); Du; Gordon (now Mouchel); Padaratz and Martin (now Arup) were all previous Group members and contributed to its developments. This group has conducted research into concrete deterioration and NDT investigation and monitoring with these key findings:

Reinforcing Steel design and corrosion monitoring.
ERPE research over the last decade addressed a range of technical issues within the topic of bond between reinforcement and concrete. This work addressed fundamental modelling of behaviour [1], new reinforcing materials, serviceability performance, strength in new construction and residual strength and degradation of deteriorating concrete structures. Of particular recent consequence has been advances in identifying corrosion-damaged structures and on fusion bonded epoxy coated reinforcement. The field work aspect of this was followed up by McCarter for a corrosion monitoring instrument [4] patent application published in 2011 as WO2011 048378 A2

Quantification of NDT Test Interpretations; instrumentation and software development.
ERPE quantified in 1995, for the first time, the accuracy of both electromagnetic GPR and stress wave impact-echo NDT identification of shallowest defects – related to signal wavelength [2]. New insights into electromagnetic wave impulse radar GPR propagation through concrete were established theoretically and verified experimentally, linking antenna centre frequency in air to wave propagation through concrete. The research clarified the relationship between antenna centre frequency and shallowest detectable target. Parallel work on stress wave propagation has brought new insights into impact echo testing of concrete. Previously, the choice of impact hammer excitation of concrete was fairly arbitrary – this work has related hammer size to signal wavelength and depth of first detectable target, funded under four Highways Agency (HA) Contracts (totalling £392k). This provided the key input to ACI document 228.2r-2013 – see [2, 3].

Testing and monitoring site measurements.
Further research into non-destructive evaluation and monitoring of concrete deterioration from 1995 developed marine and roadside test-sites under the auspices of the Transport and Road Research Laboratory and Transport Scotland. These sites allowed monitoring of concrete at near full-scale under natural environmental action. The marine test-site provided a unique database for chloride ingress (diffusivity) into concrete as chloride profiling has been continuing for almost twenty years. Through EPSRC (GR/L55810, £157k) and Transport Scotland; (£105k), an embeddable sensor system was developed which enables discretized electrical impedance (and

temperature) measurements to be obtained within the concrete cover-zone. Such measurements are directly related to those properties of concrete which promote the ingress of water and water containing deleterious ionic species, hence durability and performance [4, 5] and this was extended within Grants EP/G025096 (£361k) and EP/I005846 (£100k). The marine test-site was used to trial a remote interrogation system whereby the sensor system could be accessed from the office setting. This sensor array exploitation is now licensed to Amphora NDT.

Ground Penetrating Radar.
The theoretical and numerical focussed research on GPR modelling [6] is now well-established in practice for infrastructure monitoring and assessment with applications ranging from concrete and masonry infrastructure through to mine detection and ice cap probing. ERPE are currently enabling easy access to the software (www.GprMax.org) not only in the UK, but also to internationally based practitioners and researchers and to extending application to other areas, e.g. abandoned mineshaft detection.

3. References to the research (indicative maximum of six references)

References identified with * are those which best indicate the quality of the underpinning research.

[1] Cairns, J., Du, Y. and Law, D.W. "Structural Performance of Corrosion-Damaged Concrete Beams", ICE Magazine of Concrete Research, Vol. 60, No. 5, pp. 359-370, 2008. DOI:10.1680/macr.2007.00102 . Google Scholar (GS) 16 citations.
Guidance provided in Table 6.1-4 of the fib Model Code 2010 is based on this investigation of reinforced concrete beams with up to 8% loss of rebar cross section due to corrosion.

[2] Padaratz, I.J. and Forde, M.C. "A Theoretical Evaluation of Impulse Radar Wave Propagation through Concrete", Journal of Non-Destructive Testing & Evaluation, Vol. 12, pp. 9-32, 1995. DoI: 10.1080/10589759508952833 . GS 21 citations.
This has brought new insights into radar propagation through concrete and heavily influenced Section 3.8 of ACI 228.2r-2013 and the data forms the basis of Table 3.8.2 in ACI 228.2r-2013.

[3] Martin, J., Hardy, M.S.A., Usmani, A.S. and Forde, M.C. "Accuracy Of NDE In Bridge Assessment", Engineering Structures, Vol 20, No. 11, pp. 979-984, 1998. http://www.sciencedirect.com/science/article/pii/S0141029697001922# . GS 23 citations.
This has brought new insights into impact echo testing hammer excitation of concrete and heavily influenced Section 3.2 of ACI 228.2r-2013 and the data forms the basis of Table 3.2.3.2 in ACI 228.2r-2013.

[4]*McCarter, W.J., Emerson, M. and Ezrim, H., "Properties Of Concrete In The Cover Zone: Developments In Monitoring Techniques", ICE Magazine of Concrete Research, Vol. 47, No. 172, pp. 243-251, 1995. DOI: 10.1680/macr.1995.47.172.243 GS 46 citations.
This represents the initial development of an embeddable conductivity array to study water and ionic movement within cover-zone concrete. It is this cover-zone which plays an important role in protecting the steel reinforcement and is regarded as critical with regard to the durability of reinforced-concrete and its long-term performance.

[5]*McCarter, W.J., Chrisp, T.M., Starrs, G. and Blewett, J., "Characterisation And Monitoring Of Cement-Based Systems Using Intrinsic Electrical Property Measurements", Cement and Concrete Research, Vol. 33, pp. 197-206, 2003. DOI: 10.1016/S0008-8846(02)00824-4 . GS 43 citations.
The research highlights the use of electrical property measurements to study, for example, the hydration and hydration kinetics of cementitious materials and the response of the concrete cover-zone to cyclic wetting and drying.

[6]* Giannopoulos, A., "Modelling Ground Penetrating Radar By GprMax", Construction and Building Materials, Vol. 19, pp. 755–762, 2005. DOI: 10.1016/j.conbuildmat.2005.06.007 . GS 160 citations.
This summarises more than 10 years research into a solver for GPR: GprMax, which is now the most widely used GPR modelling software and an industry standard.

4. Details of the impact (indicative maximum 750 words)
The deterioration of concrete structures is of world-wide concern. In the UK, the total construction industry investment in 1995 was £52 billion, with 50% spent on maintenance, repair etc., representing a threefold increase over the previous 14 years. The £28M Birmingham Midlands link motorway required £45M of repairs between 1972-89 and then required a further £120 million investment up to 2004. In continental Europe, structural repairs cost €1.4 billion p.a. In 1998, US estimated a five-year investment of $1.3 trillion to reinstate roads, bridges and other infrastructure systems to good serviceable life. This had increased, by 2005, to $1.6 trillion, as in excess of 40% of 500,000 highway bridges are rated as structurally deficient requiring $100 billion to eliminate the bridge backlog.

The ERPE work on Non Destructive Testing (NDT) has been accepted internationally by the American Concrete Institute (ACI 228-2r-2013), and by international manufacturers such as Sensors and Software who use GPR max software to design their new generation of GPR antennas. This has brought new insights into electromagnetic wave impulse radar GPR propagation through concrete by linking antenna centre frequency in air to wave propagation through concrete. It has clarified the relationship between antenna centre frequency and shallowest detectable target. This has heavily influenced Section 3.8 of ACI 228.2r-2013 and the data forms the basis of associated Table 3.8.2. The work on stress wave propagation has brought new insights into impact echo testing of concrete. Previously the choice of impact hammer excitation of concrete was fairly arbitrary – this work has related hammer size to signal wavelength and depth of first detectable target. ERPE research has changed industry thinking by heavily influencing Section 3.2 of ACI 228.2r-2013 and our data forms the basis of Table 3.2.3.2.

"As Principal and Manager of our international group NDT practice in Dynasty Group I can verify that the ERPE work led by Forde has established new understandings of the accuracy and effectiveness of NDT techniques such as radar testing of concrete, masonry and railway trackbed, plus impact echo testing. This highly innovative world leading work has influenced the technical success of our own company and has achieved international impact through its inclusion in the American Concrete Institute's ACI 228.2r-2013 "Report on Nondestructive Test Methods for Evaluation of Concrete in Structures". Forde led the drafting of this world standard in Civil Engineering concrete NDT over 8 years and I was a voting member of the ACI 228 Committee."
Principal, Dynasty Group, USA [S1].

The ERPE work led by McCarter developed the use of electrical property measurements to study the hydration and hydration kinetics of cementitious materials and the response of the concrete cover-zone to cyclic wetting and drying key areas when assessing concrete corrosion. The field implementation of this work of this was implemented by McCarter when he developed a corrosion monitoring [4] instrument: UK Patent application WO2011 048378 A2 which was licensed in 2013 to Amphora NDT Ltd (sold under the trade name Septopod: http://www.amphorandt.com/septopod.html) and has recently been installed on the Hangzhou Bay Bridge in China [S5].

"I can confirm that the long-term leading research on the performance of concrete in extreme marine environments is of major importance to the international bridge community. This work, partially funded by us for 20+ years has led to a patent pending NDT instrument manufactured and marketed by Amphora NDT, with sales in China. Further development of the sensor array & retrofitting in a variety of Trunk Road environments has expanded the applicability of the technology & provides confidence of ongoing structural performance. This is an excellent example of research fulfilling the needs of bridge owners and providing an instrument to monitor important on-site durability issues worldwide" - Network Bridges Manager, Transport Scotland [S2].

The ERPE radar (GPR) modelling work [6] over 10 years led Giannopoulos to write the world's most widely used Finite Difference Time Domain (FDTD) forward modelling program (some 4,000 downloads) which has had a worldwide impact on improving both the accuracy of interpretation of radar surveys by service providers and also on the manufacturers design of antenna systems:

"As CEO of Sensors & Software, the world's leading manufacturer of GPR (ground penetrating radar) equipment, I can confirm that the world's leading GPR modelling software is GprMax which is used by industry and researchers worldwide. Here we use it for modelling to help us improve our antennae for the worldwide market and we confidently state that it is increasing our turnover and profit." Senior Manager Sensors & Software Inc, Canada [S3].

Concrete design research in ERPE, has made a significant contribution to the fib (fédération internationale du béton) Model Code (MC2010), (fib 2013) [Ernst & Sohn, Berlin, Oct 2013, ISBN: 978-3-433-03061-5 and http://www.fib-international.org/model-code-2010-final-draft-volume-1] Cairns, as convenor of Task Group 4.5 (TG4.5) 'Bond Models', was responsible for drafting Section 6.1 'Bond of embedded reinforcement' and sub-sections 7.13.2.5-6 within 'Detailing'. The previous version of this fib Model Code formed the basis for Eurocode 2 (http://www.concretecentre.com/codes_standards/eurocodes/eurocode_2.aspx), the design standard for Europe. These Model Codes provide industry rules which assist them today in the design of safe, constructible and economic concrete structures. ERPE innovations include:

- Modified design rules to cater for: (a) new high performance concrete (C100/125); (b) new materials and technologies with differing bond and anchorage capabilities – e.g. fusion bonded epoxy coated reinforcement and headed bars.
- Guidance has been introduced on the load carrying capacity of concrete structures following a period of deterioration or following repair.
- Inconsistencies in MC90 design rules have been addressed, e.g. statistical analysis has demonstrated an insignificant difference in bond strength between lapped joints and of anchorages, but design rules in MC90 treat laps and anchorages as different. MC2010 has resolved these issues.

"As a colleague on fib Task Group 4.5 (TG4.5) 'Bond Models' code of practice I confirm that Cairns has been responsible for a major review and updating the technical content covering the bond between embedded reinforcement and concrete and that those revisions now provide a more rational evidence based approach. He is also leading production of a fib Bulletin which records the rationale and evidence for these revisions which will be published in 2014." Italian TG4.5 committee member [S4].

Other documents, based on ERPE research, are current and are still impacting international industrial practice today:

BA86/06 Advice Notes on the Non-Destructive Testing of Highway Structures, Highways Agency (HA), Design Manual for Roads & Bridges, Vol. 3, Section 1, Part 7, 2006, 247 pp.

IAEA (2002) Guidebook on Nondestructive Testing of Concrete Structures, IAEA-TCS-17, Austria, Sept 2002, 231 pp.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Principal and Manager of NDT, Dynasty Group Inc., see comments included in Section 4.

[S2] Network Bridges Manager, Transport Scotland, see comments included in Section 4.

[S3] Senior Manager, Sensors & Software Inc. , see comments included in Section 4.

[S4] Member of the Task Group 4.5 Committee, see comments included in Section 4.

[S5] Deputy Chair of Chinese construction committees can confirm the sensor system installation on Hangzhou Bay Bridge in China.