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# Design of durable concrete structures

Stuart Matthews

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Registered office: Willoughby Road, Bracknell, Berkshire RG12 8FB.
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BRE Trust publications are available from
www.brebookshop.com
or
IHS BRE Press
Willoughby Road
Bracknell
Berkshire RG12 8FB
Tel: +44 (0) 1344 328038
Fax: +44 (0) 1344 328005
Email: brepress@ihs.com



Printed using FSC or PEFC material from sustainable forests.

Printed in Great Britain by Bell & Bain Ltd, Glasgow

**FB 70**

**First published 2014**

**ISBN 978-1-84806-175-0**

*Front cover photograph:* Rio-Antirrio Bridge (also called Charilaos Trikoupis Bridge) near Patras, Greece

*Back cover photograph:* The Aquatics Centre, London 2012 Olympic Park

Index compiled by Cathryn Pritchard

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# Preface

This document seeks to give an appreciation of the wide range of issues associated with the design of durable concrete structures, and matters concerned with service life design. The material reported here is drawn from many sources, which have, it is hoped, been adequately acknowledged. The document attempts to reflect recent and evolving developments, and thereby give an up-to-date overview on matters concerned with service life design. This is a process whose overall objective is to ensure that the concrete structure concerned achieves appropriate durability – which is one of the primary functional requirements that the design and construction process should be expected to deliver.

The document contains 19 main chapters:

1 Introduction
2 Overview of the service life design, construction and through-life care process
3 Through-life performance, life-cycle cost and sustainability
4 Mechanisms that may cause deterioration or damage to concrete structures
5 Some factors influencing the durability of concrete structures
6 Environmental aggressivity
7 Recommendations in standards and codes of practice
8 Overview of modelling of deterioration processes
9 Factorial approach to estimating service life
10 Service life design process and considerations
11 Measures to enhance resistance or avoid reinforcement corrosion
12 Measures to enhance resistance and avoid deterioration
13 Influence of some design, execution and workmanship issues on durability
14 Construction quality issues: the role of the project execution specification
15 Improving durability: benefits of pre-construction planning and trials
16 Condition control: planned through-life structure management and care
17 Monitoring of durability and performance
18 Examples from practice
19 Future look: potential developments influencing service life design

This publication is an updated and significantly extended version of Volume 3 (Chapter 5) of the second edition of the *fib Structural concrete textbook*, which deals generally with the behaviour, design and performance of structural concrete. Volume 3 of the second edition of the *fib Structural concrete textbook*, which was published as *fib* Bulletin 53 in December 2009, is concerned with the design of durable concrete structures. Stuart Matthews prepared *fib* Bulletin 53, which was an updating and extensive further development of the chapter on durability prepared by Dr Steen Rostam that formed part of the original *fib Structural concrete textbook*, and was published as part of *fib* Bulletin 3 in 1999.

This updated and extended version takes account of subsequent developments in *fib* Model Code 2010 for the design of concrete structures between the early committee draft versions available when *fib* Bulletin 53 was produced and the final version due for publication in 2012, as well as those in related areas of service life design for concrete structures, such as those associated with ISO/DIS 16204. Account has also been taken of recent technical activities within groups such as *fib* Commission 5: Structural service life aspects. Other revisions and additions include further developments associated with topics such as the through-life management and care of concrete structures (Chapters 2 and 3), the diversity in views on the effect of cracks in concrete upon durability (Chapter 5), and the potential future influence of sustainability on service life design considerations (Chapter 19). In addition, various amendments have been made to the earlier text to reflect specific aspects of UK technical practice and guidance in this area (particularly BS 8500 and associated standards).

*Chapter 1* provides an introduction and sets out the scope of the issues, providing an overview of the document. It notes that modern concrete forms a family of materials, and seeks to indicate why durability of concrete structures is important. It reviews previous experience in terms of the in-service performance of concrete structures, and the need to take a holistic view when creating durable concrete structures. The chapter also notes the importance of variations in concrete properties and the durability-critical role of the cover concrete, and outlines some simple conceptual models for the deterioration

caused by the corrosion of reinforcement. It introduces the benefits of considering through-life performance, life-cycle cost and sustainability perspectives when undertaking outline service life design and developing durability and service life design concepts. The chapter provides definitions and terminology, before giving an overview of the various approaches to service life design and drawing parallels between contemporary structural and probabilistic-based service life design concepts.

*Chapter 2* builds on Chapter 1 to provide an overview of the service life design, construction and through-life care process. It examines the role and importance of the client brief and the definition of performance expectations, before headlining environment aggressivity classification, conceptual and detailed design for durability, and the deemed-to-satisfy durability solutions design given in codes and standards. The chapter introduces the concept of probabilistic, performance-based service life design, before examining the way in which project specifications can be used by clients and owners as a tool to achieve the desired durability, and the importance of the execution of the construction works for through-life care and maintenance aspects.

*Chapter 3* examines through-life performance, life-cycle cost and sustainability issues, and seeks to draw out wider societal sustainability perspectives, as well as consideration of life-cycle cost issues.

*Chapter 4* reviews mechanisms that may cause deterioration or damage to concrete structures. It provides an overview of deterioration and damage mechanisms (but excludes damage arising from accidental actions), and outlines the role of water and moisture transport mechanisms in this. The chapter looks in detail at mechanisms that may cause deterioration or damage, classifying these into four groups: those causing physical deterioration and damage processes in concrete; those associated with chemical deterioration processes; those associated with biological deterioration processes in concrete; and the corrosion of reinforcement. Consideration is briefly given to deterioration mechanisms acting in combination.

*Chapter 5* reviews some factors that influence the durability of concrete structures. These include the geometrical form and architectural detailing of the structure; the cement type, mix design and concrete quality; the reinforcement type, and the depth and quality of the concrete cover; together with the potential influence of cracking, crack width and crack orientation.

*Chapter 6* examines issues associated with environmental aggressivity, looking at moisture-driven deterioration processes, atmospheric-induced deterioration, the role of temperature-induced effects, and a contemporary system for the classification of environmental exposure.

*Chapter 7* reviews the recommendations made in some standards and codes of practice, looking at those given in the CEB-FIP Model Code 1990 (CEB-FIP, 1992) and the *fib* Model Code for Service Life Design (*fib*, 2006b) (published in *fib* Bulletin 34), together with the guidance given in BS EN 1992 *Concrete structures* (Eurocode 2, BSI, 2004 – 2006) and associated product standards. The approach and content of *fib* Model Code 2010 (*fib*, 2012b) and ISO 16204 (ISO, 2012) are also examined.

*Chapter 8* provides a brief overview of the modelling of deterioration processes, with the main focus being on carbonation and chloride-induced corrosion of reinforcement in uncracked concrete. Consideration is also given to the modelling of other mechanisms of deterioration, such as frost attack, sulfate attack, alkali–aggregate reaction, leaching and surface weathering, and abrasion by ice. The application of deterministic and probabilistic models is discussed, together with the partial factor method. The results for reinforcement corrosion obtained from a deterministic service life design model are compared with those from a probabilistic model.

*Chapter 9* explains the use of the factorial approach to estimating service life, making reference to a process used for combining additional protective measures to extend service life.

*Chapter 10* examines the service life design process and related considerations, outlining the main steps in a service life design procedure, and the approaches that may be adopted for detailed service life design, together with the definition of the target service life and environmental aggressivity. The various steps in the overall service life design procedure are introduced, but with more detailed discussion being provided about the adoption of a multi-layer protection approach, with an example of this concept being given for multi-layer protection of prestressing tendons, as given in *fib* Bulletin 33 (*fib*, 2006a). Additional observations are made for durability and service life design issues for environments where de-icing salt is applied, and for structures in a marine environment. The concepts associated with Birth Certificate documentation and reliability updating are also explained.

*Chapter 11* presents detailed recommendations for measures to enhance resistance or avoid reinforcement corrosion on the basis of the selection of cementitious materials, the use of admixtures and fibres, ways of enhancing the resistance of the surface of the concrete, ways of enhancing tolerance to carbonation and chlorides, and the avoidance approach (ie the design-out approach). The chapter concludes with an overview of measures to enhance resistance or avoid reinforcement corrosion.

*Chapter 12* summarises some measures to enhance resistance or avoid forms of deterioration other than reinforcement corrosion.

*Chapter 13* examines the influence of some design, execution and workmanship issues on the durability of concrete structures. The matters considered include: the influence of locally available concrete materials and labour; dimensioning of structural elements; reinforcement detailing and congestion; compaction and curing of concrete; the use of controlled-permeability formwork, self-compacting concrete and high-performance concrete; durability problems associated with spacers and chairs to support reinforcement; and the use of inserts and fixtures. The benefits of using of stainless steel reinforcement, the role of quality assurance and quality control, and the potential importance of aesthetics and appearance issues are discussed.

*Chapter 14* examines construction quality issues and, in particular, the role of the project execution specification in creating greater certainty of achieving durable concrete structures. The approach adopted is centred on the European construction standards and the Execution Standard (BS EN 13670; BSI, 2009d), with observations being made about how these link with the quality management standards contained in the ISO 9000 series.

*Chapter 15* discusses the potential benefits of pre-construction planning and trials as a means of improving the durability of concrete structures, particularly for major infrastructure projects. Six steps to delivering improved certainty of achieving durable concrete construction are set down.

*Chapter 16* describes the condition control processes that may be adopted for planned through-life structure management and care, linking these into an overall process of condition survey and monitoring activities, condition assessment and condition evaluation. These are based on the concepts developed in the work undertaken for Chapter 9: 'Conservation' of *fib* Model Code 2010 (*fib*, 2012b). This chapter outlines the role of classes of condition control within the process of through-life management of a structure, describing the associated condition control levels and inspection regimes. While a strategy using proactive condition control measures is recommended for new concrete structures, the approach outlined allows for reactive condition control measures, and for situations where condition control measures are not feasible (ie foundations).

*Chapter 17* describes methodologies for monitoring the durability and performance of a concrete structure. It provides advice on the locations for surveys, testing and monitoring activities, condition survey and monitoring activities, tools and techniques for surveys, and monitoring and data gathering for condition control purposes. As with Chapter 16, the approach is based on the concepts developed in the work undertaken for Chapter 9: 'Conservation' of *fib* Model Code 2010. The chapter also briefly considers issues associated with the automated monitoring of concrete structures, and how these techniques can link to the updating of service life predictions.

*Chapter 18* presents details of two service life design examples from practice: the Great Belt Fixed Link, Denmark, and the Western Scheldt Tunnel, the Netherlands.

*Chapter 19* provides a future look, examining some potential developments that may influence durability and service life design in the future. The topics considered include the *fib* Model Code 2010, the need for improved scientific understanding of deterioration processes, anticipated developments in cementitious and concrete materials, and the further development and application of service life design principles.

The document concludes with extensive lists of references and further reading.

# Acknowledgements

The author gratefully acknowledges the financial support provided by BRE Trust for elements of the background work employed in this publication. The publication also draws on work undertaken in BRE research and related projects over recent years.

The author wishes to thank *fib* and other colleagues for their input to discussions supporting the development of the ideas and material presented here, in *fib* Bulletin 44 (2008) and in other work; plus access that has been obtained to various other sources of technical information for use in this publication. Particular thanks go to C Andrade (especially in relation to aspects of Chapter 4), A Bigaj-van Vliet (in relation to Chapter 16), J Buffenbarger (in relation to the results of the comparative study of ternary and other powder blend concretes reported in section 11.2.7), C Clear, M Clift, S Curtis (particularly in relation to Chapters 14 and 15 and the Appendix), C Gehlen, J Gulikers, S Helland, S Rostam and T Ueda (in relation to Chapter 16) for the material that they have made available. The author also wishes to thank *fib* for permission to reproduce Figures from various *fib* Bulletins.

The author is particularly indebted to BRE colleagues for access to material prepared in respect of BRE publications, and also to that produced during the BRE service life research project. The author has drawn freely on this compendium of work, and acknowledges the valuable assistance that this material has given in the preparation of this publication. Particular thanks go to Phil Bamforth, Éanna Nolan and Keith Quillin for the material that they have made available. Special thanks also go to the BRE librarians Marian Bodian and Susanne Woodman for their assistance in researching literature sources and obtaining copies of the required information, along with Nick Clarke of IHS BRE Press for his efforts in the process of editing and updating the original *fib* Bulletin 53 version of the document.

The author is very grateful to the following individuals and organisations for making available photographs and images used in this document: C Andrade, U Angst, S Curtis, C Edvardsen, A Knudsen, M Raupach, I Stipanovic Oslakovic, G Thielen, Arminox, BRE, CIRIA, *fib*, IHS BRE Press, the Concrete Society and UK CARES. Also of note is the assistance of Adam Hughes of IHS BRE Press in the resourcing and processing of digital images.

The Concrete Society has permitted the reproduction of the figures listed below from its publications, with thanks to R Day and J Clarke for their assistance in sourcing various items. These figures are reproduced with permission of the Concrete Society from the publications cited in the references and bibliography, which are available to purchase from *www.concretebookshop.com*. Copyright for these figures is retained by the Concrete Society. The figures reproduced are Figures 1.10, 4.3, 4.10, 4.16, 5.2, 5.5 to 5.7, 11.1 to 11.9, 11.17 to 11.20, 14.2 and 14.3.

The author is also indebted to the colleagues who undertook the task of reviewing the original *fib* publication (published as *fib* Bulletin 53) and the current publication and for their helpful comments, especially Carmen Andrade, György Balázs, Nick Clarke and Keith Quillin.

The author wishes to acknowledge Steen Rostam, the author of the chapter on durability in the original *fib* Textbook on Structural Concrete published as part of *fib* Bulletin 3, who passionately promoted consideration of matters relating to durability and the service life design of concrete structures.

And finally, apologies to any of the numerous people who have assisted me in the task of creating this publication that I may have inadvertently overlooked in this list of citations.

# About the author

Stuart Matthews is currently Chief Engineer Construction, BRE, and was formerly Director of the Centre for Concrete Construction at BRE. He is a Chartered Engineer, a Chartered Scientist and a Chartered Water and Environmental Manager and has extensive experience in the fields of civil engineering and building, having been in practice for over 35 years. He worked for a range of organisations, including a water authority, a contractor, a consultant and a specialist test house, before joining BRE to undertake research and consultancy in a range of areas.

Stuart has been involved in the design and construction of concrete infrastructure, service life and durability issues for concrete structures, including various types of nuclear industry structures, plus methods for their investigation, assessment, repair and refurbishment. Other topics have included non-destructive testing techniques, the use of marine aggregates, and work on the sustainability/environmental impact evaluation of concrete materials.

He is actively engaged in the work of several professional, national and international organisations and technical committees. Among others, he is currently co-chair of *fib* Special Activity Group 7 on the assessment of existing structures. He previously convened *fib* Commission 5 concerned with the service life design, assessment and rehabilitation of concrete structures. He was also closely involved in the work of *fib* Special Activity Group 5, which was responsible for the preparation of *fib* Model Code 2010, published in early 2012.

He is the author or principal author of *fib* Bulletins 53 and 62, BRE Report 511, and BRE Digests 366 (2012), 510 and 526; as well as being a main contributor to the CONREPNET project report EP77 and *fib* Bulletin 44. He also contributed extensively to the second (1996) and third (2010) editions of the Institution of Structural Engineers' report *Appraisal of existing structures*, to *fib* Bulletin 17 and *fib* Model Code 2010, and to the *ICE Manual of Structural Design* (2012), contributing the chapter on 'Taking a through-life perspective in design'. In addition, Stuart is the author or joint author of numerous technical papers and other publications.

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# Abbreviations

| | |
|---|---|
| AAR | alkali–aggregate reaction |
| AC | alternating current |
| ACEC class | aggressive chemical environment for concrete class |
| ACI | American Concrete Institute |
| AFRP | aramid fibre-reinforced polymer |
| ASR | alkali–silica reaction |
| BCA | British Cement Association |
| BRE | Building Research Establishment Ltd |
| BS | British Standard |
| BSI | British Standards Institution |
| CABE | Commission for Architecture and the Built Environment |
| CAC | calcium aluminate cement |
| CAL | condition assessment level |
| CARES | Certification Authority for Reinforcing Steels |
| CC | consequence class |
| C&CA | Cement and Concrete Association |
| CCL | condition control level |
| CE | CE Mark |
| CEB | Comité Euro-International du Béton [European Committee for Concrete] |
| CEN | Comité Européen de Normalisation [European Committee for Standardisation] |
| CFRP | carbon fibre-reinforced polymer |
| CIB | Conseil International du Bâtiment [International Council for Research and Innovation in Building and Construction] |
| CIRIA | Construction Industry Research and Information Association |
| CONREPNET | Thematic network on performance-based remediation of reinforced concrete structures: CONcrete REPair NETwork |
| CONTECVET | A validated user's manual for assessing the residual service life of concrete structures |
| CoV | coefficient of variation |
| CPD | Construction Products Directive |
| CPF | controlled-permeability formwork |
| CPR | Construction Products Regulation |
| CSMA | Cementitious Slag Makers Association |
| DARTS | durable and reliable tunnel structures |
| DC class | design chemical class |
| DEF | delayed ettringite formation |
| DSL | design supervision level |
| EA | environmental aggressivity |
| EC | European Commission |
| EDC | equivalent durability concept |
| EDP | equivalent durability procedure |
| ECPC | equivalent concrete performance concept |
| EN | European Norm (a European Standard) |
| ENV | European Pre-standard (voluntary use) |
| EPCC | equivalent performance of combinations concept |
| ERMCO | European Ready-Mixed Concrete Organisation |
| ESLC | estimated service life |
| EXC | execution class |
| fa | Fly ash: see pulverised fuel ash |
| FBECR | fusion-bonded, epoxy-coated reinforcement |
| *fib* | Fédération Internationale du Béton [International Federation for Structural Concrete] |
| FIP | Fédération Internationale de la Précontrainte [International Federation for Prestressing] |
| FRP | fibre-reinforced polymer |
| ggbs | ground granulated blastfurnace slag |
| GHG | greenhouse gas |
| GRC | glass-fibre-reinforced concrete |
| GRCA | Glassfibre Reinforced Concrete Association |
| HAC | high-alumina cement |
| hEN | harmonised European Norm (European technical standard) |
| HETEK | high-quality concrete, the contractor's technology (Danish research project) |
| HPC | high-performance concrete |
| HRWRA | high-range water-reducing admixture |
| HSC | high-strength concrete |
| IABSE | International Association for Bridge and Structural Engineering |
| IBA | incinerator bottom ash |
| IBAA | incinerator bottom ash aggregate |
| ICE | inventory of carbon and energy; Institution of Civil Engineers |

| | |
|---|---|
| ISE | Institution of Structural Engineers |
| ISO | International Organization for Standardization |
| LCA | life-cycle analysis/assessment |
| LCC/LCCA | life-cycle cost/life-cycle cost analysis |
| LIFECON | life-cycle management of concrete infrastructures for improved sustainability, competitive and sustainable |
| LIFECON LMS | life-cycle management of concrete infrastructures for improved sustainability, competitive and sustainable |
| LMS | life-cycle maintenance and management planning system |
| LPR | linear polarisation resistance |
| MADA | multi-attribute decision aid |
| MC | (CEB-FIP) Model code |
| MCDM | multiple criteria decision making |
| MC-SLD | (*fib*) Model Code for Service Life Design |
| MFU value | most frequently used value |
| mk | metakaolin |
| MMFX | microcomposite multistructural formable |
| MPA | Mineral Products Association |
| NANDO | New Approach Notified and Designated Organisation |
| NDP | nationally determined parameter |
| NDT | non-destructive testing |
| PBA | performance-based approach |
| PC | Portland cement |
| PDF | probability distribution function |
| pfa | pulverised fuel ash: see fly ash |
| PL | protection level |
| prEN | pre-normative European Standard (a provisional standard issued for comment) |
| PREN | pitting resistance equivalent number |
| QA | quality assurance |
| QC | quality control |
| QFD | quality function deployment |
| QSRMC | quality scheme for ready mixed concrete |
| RA | recycled aggregate |
| RAMS | reliability, availability, maintainability and safety |
| RC | reliability class |
| RCA | recycled concrete aggregate |
| RH | relative humidity |
| ROC | robustness class |
| RSLC | reference service life |
| SBR | styrene-butadiene rubber |
| SCC | self-compacting concrete |
| SCC | stress corrosion cracking |
| SCE | saturated calomel electrode: mercurous chloride |
| SCF | Sustainable Concrete Forum |
| SCM | secondary cementitious material |
| sf | silica fume or microsilica |
| SLD | service life design |
| SLS | serviceability limit state |
| SM | safety margin |
| TR | technical report |
| TSA | thaumasite form of sulfate attack |
| UKQAA | UK Quality Ash Association |
| ULS | ultimate limit state |
| w/b | water/binder (ratio) |
| w/c | water/cement (ratio) |
| WLC | whole-life cost |
| ZRA | zero-resistance ammetry |