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Design of durable concrete structures

Stuart Matthews

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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.

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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.

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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.

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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.

Contents

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.

1 Introduction

1.1 Background

Concrete is the most extensively used construction material (in terms of annual tonnage used). It has been used successfully for an innumerable number of buildings and structures for almost 2000 years. It has shown that it can be a very durable material. For example, the Pantheon in Rome was rebuilt in the early second century (completed 126 AD) using Roman concrete. The building acted originally as a Roman temple, and is still being used today as a working church: see Figure 1.1. However, it should not be assumed that concrete has everlasting properties, or that all concretes will be durable in all circumstances. These issues are the focus of this document.

The introduction of reinforcing steel dramatically improves the tensile strength of concrete, enabling slender structures to be built with much longer spans and higher working stresses. Most of today's concrete construction relies on the composite interaction of concrete and steel, which is aided by the near equivalence of their thermal expansion characteristics.

Structural (reinforced) concrete made from Portland cement has dominated the construction environment for the last 100 years or so. One of the reasons for this success is that concrete is very adaptable, in that it can be cast into almost any shape or form. Today concrete provides a unique building material for the majority of structures worldwide.

With correct design, specification and construction, concrete structures provide high-performing, durable assets with long service lives. The vast majority of concrete structures perform satisfactorily, and are adequately durable for their service environment.

True (2012) in his extensively illustrated book, *Decorative and innovative use of concrete*, provides many examples of buildings and structures, some iconic, which are generally performing well with time. He describes the numerous ways in which concrete can be or has been formulated, along with the finishes employed in the final work, to provide many examples of high quality buildings and structures, some of which have achieved iconic status. The examples presented provide an understanding as to what is possible with the material and illustrate how designers from all over the world have been able to capitalise on the properties of concrete such as its mouldability. True (2012) explores the material's history (from ancient Egypt to present day) and the technical background of both material and design solutions adopted by many of the key 20th and 21st century architects and engineers from all over the world. In doing so, True (2012) presents a cornucopia of concrete exemplars.

It is clear that the future development of the world economy will require significant investment in a wide range of assets and buildings and other industrial facilities in many different geographic areas and climatic zones, but particularly in energy generation and transport infrastructure. This will involve the creation of a diverse range of long-life, and in some cases ultra-long-life, assets. Energy generation and transport infrastructure will potentially include facilities such as nuclear power plants, barrages for electrical energy generation, offshore wind turbine farms, bridges, tunnels, structures for offshore installations, and many more – all of which will be situated in extremely aggressive environments, and will be subject to very demanding performance requirements. Durability will be an important consideration.

These facilities will require a diverse range of concrete structures, which will involve the use of large volumes of different types of concrete. In these developments it will be important to get an appropriate balance between potentially conflicting requirements associated with matters such as functional performance, adequate durability (to achieve the long design service life needed with many types of infrastructure), long-term holistic sustainability issues, life-cycle cost, and effective through-life management of these assets. With long-life assets it is necessary to achieve a balance between these influencing factors different from that associated with other forms of construction that have a shorter life and lower expectations for long-term durability, such as housing and conventional buildings.

Figure 1.1: The Pantheon, Rome. *The interior of the Pantheon*, Giovanni Paolo Panini (images courtesy of Wikimedia Commons)

Concrete structures also make a significant contribution to the resilience of the stock of buildings and the extensive infrastructure on which modern society increasingly relies. Neale (2012) has drawn attention to the breadth of the considerations which may apply to various types of infrastructure, especially where they are situated in different geographic locations. Each is typically subject to different performance expectations and exposure to dissimilar naturally occurring and manmade hazards.

In recent years a number of high-profile natural disasters, industrial accidents and other events, such as terrorist incidents, have highlighted the importance of resilient buildings and infrastructure systems and, in particular, planning for high-consequence/high-impact, low probability events. The objective is that resilient buildings and infrastructure should be able to continue to provide basic safety and performance functions after a disaster event, even if the level of performance may be restricted depending on the severity and circumstances of the event. Resilience helps with disaster risk management and consequence reduction, which are increasingly significant factors when planning for a future sustainable society.

In addition to characteristics such as robustness and endurance, other important considerations, especially for critical long-life assets, include their durability and longevity. These matters are discussed further in Section 1.12.

Around the world, concrete has provided a very adaptable means of creating the facilities and assets necessary to meet the needs of society. This has been done largely by using the locally available material resources (ie sand and rock as fine and coarse aggregates, water). This is a great advantage. Thus concrete can be tailor-made for a great variety of uses; it can be made almost anywhere, and from a host of indigenous materials. So far, concrete has been made mainly using Portland cement as the binder.

Such concrete has a significant amount of embodied carbon dioxide (CO_2), as the manufacture of Portland cement involves sizeable CO_2 emissions, but the future use of alternative cements (which are currently under development) could reduce this substantially. These changes and developments will undoubtedly pose new and different challenges in respect of the design

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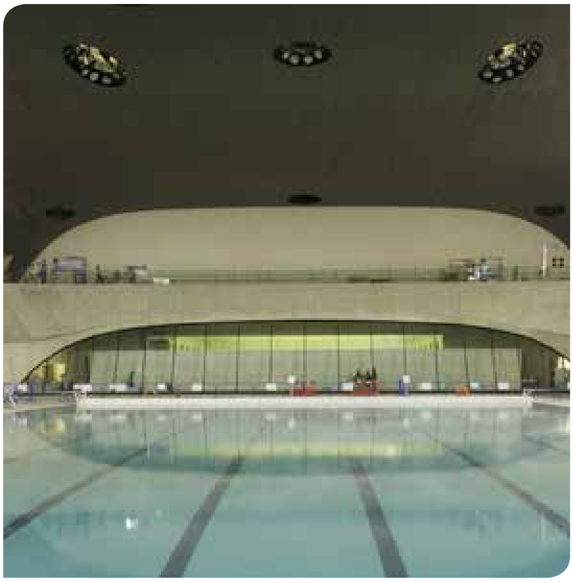
Design of durable concrete structures

This book provides an understanding of the complex set of phenomena governing durability and long-term performance of concrete structures, and how these form a basis for service life design. While consideration is given to concrete as a material, the focus is on the behaviour of the concrete structure and its interaction with its environment.

The book will not only assist the designer to improve the future durability performance and reliability of concrete structures, but will also assist engineers involved with the assessment, maintenance and extension of life of existing concrete structures.



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