PROBABILISTIC DURABILITY DESIGN AND PERFORMANCE-BASED SPECIFICATION OF CONCRETE IN THE MARINE ENVIRONMENT

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Abstract

The required or intended “service life” of a structure is a major factor in the design for concrete durability, and may even dictate how the overall design of a structure is approached. The longer the expected life of a structure, the greater the durability (and hence quality) of the concrete required.

Performance design and testing is a useful method to overcome the shortcomings of traditional prescriptive specifications and possibly lead to improvements. Most significantly, performance testing and design provides an additional degree of robustness for designs for prestige or strategically critical structures.

This paper provides an introduction to performance-based design and includes discussion on the approach to effective durability design for extended service lives of structures for long design lives in extreme environments.

A case study is presented where a full probabilistic design was undertaken for reinforced concrete sub-structures and superstructures for a large crossing in the Far East (project not disclosed) using a range of protective measures and best practice concrete technology. Commentary is given on probabilistic durability modelling for the ingress of chlorides to a defined Serviceability Limit State, for an intended service life of 120 years in an aggressive marine environment. Specified durability performance tests are discussed as a means to demonstrate concrete performance during construction.

Keywords: durability design, modelling, chloride ingress, marine concrete, maritime environments, reinforced concrete

1. INTRODUCTION

The required or intended “service life” of a structure is a major factor in the design for durability; the longer the expected life, the greater the required resistance to mechanisms of deterioration, and hence the greater the required durability (and thus quality) of the concrete.

Durability design for concrete structures exposed to long-service lives and/or aggressive environments needs to be an integrated part of a structured design process. Too often, durability design is seen as an after-thought and left to the last minute.

The design process should be iterative, refining performance characteristics and structural function, and encompass the use of locally available constituents where possible. The method
should provide a structured, cohesive and defensible approach to the design for concrete durability.

Two principal routes for undertaking durability design are typical:

- The prescriptive (or “deemed-to-satisfy”) approach relies on current National Standards and guidance to arrive at specific limiting proportions for concrete mix constituents, proportions and cover for a given service life and exposure, commonly stated in published tables (e.g. BS EN 206, BS8500[1]). The requirements in these tables are defined on the basis of practical experience and (consensus) judgement.

- The performance approach aims to achieve measures that demonstrate the suitability of the concrete and its constituents for a given environment and for an explicitly given design life. The durability performance parameters are often derived by performance testing and track record, or by durability modelling. In its purest form, performance-based designs are not restricted by limiting the proportions of concrete constituents.

Current UK practice is a mixture of mainly prescriptive elements (using limiting proportions and cover to define durability) combined with criteria for which performance may be implied (such as compressive strength, cover and consistence). The “deemed to satisfy” approach of prescriptive designs does not ascertain “what” the failure of a structure (i.e. its limit state) actually corresponds to, whether it is intervention by repairs or complete collapse; this is a significant failing in the prescriptive approach currently adopted by most Standards. Performance design and testing is a useful method to overcome the shortcomings of traditional prescriptive specifications and possibly lead to improvements in the understanding of concrete durability and its place in the design method for structures.

2. PERFORMANCE BASED DURABILITY DESIGN

The definition of a performance-based approach to durability can be described simply that concrete materials shall be designed and specified on the basis of their demonstrated ability to adequately perform in a given environment for a specified time period. The design life should not be less than that required by the client but may be longer to account for uncertainties, or to increase the probability of achieving the required service life.

The concept of design life requires the end of the design life to be identified. This is normally defined by attributing a degree of damage caused by the deterioration process (e.g. cracking or spalling of concrete due to reinforcement corrosion). For the durability design of concrete, the Serviceability Limit State (SLS) is normally considered most appropriate, indicating service failure or a time of major intervention, as opposed to the Ultimate Limit State (ULS) which implies failure or collapse of the structure.

Idealistically, performance based designs should start off as conservative assumptions, but with time and experience, monitoring of structures should allow quantitative updating of these assumptions to enable them to become more accurate throughout the life of the structure. Further development of performance models is only possible by continual monitoring and assessment of performance throughout the life of the structure, providing a more accurate estimate of residual life and a more robust performance model for future designs. This approach not only benefits our understanding of temporal and spatial deterioration of structures, but actually benefits the management of the structure itself, ensuring pre-emptive works are carried out in a timely manner. However, this approach rarely occurs in reality.
One of the disadvantages of performance related tests over the more traditional approach is that durability data is less likely to be available and may require extended time periods to determine actual performance, particularly in high performance concretes. It is therefore important when undertaking performance-related designs that include test programmes that sufficient lead-in times are allowed for within the construction programme to ensure performance results can be adequately utilised in the design as intended.

3. DURABILITY MODELLING

Performance-based designs may or may not include the use of modelled predictions of deterioration mechanisms as part of the design. Modelling of degradation mechanisms allows a level of robustness for the quantification of a performance-based design, particularly if performance test parameters fit well with real-life data.

The concept of durability modelling attempts to establish whether the environmental load on a structure at a given exposure condition exceeds the resistance of the structure, and may give an estimate of when it is exceeded to a defined limit state.

Figure 1 below illustrates the input distributions for load, S, and resistance, R. Random sampling of these input distributions is undertaken to provide an output distribution (the service life distribution, Z) that is then be assessed statistically to give estimates of the service period (tp) for a given limit state failure probability.

![Figure 1: Service period (tp) and lifetime design (courtesy of CIRIA)](image)

Figure 2 illustrates a simple approach assuming normal input and output distributions. The approach to reliability analysis for concrete durability is in line with the concepts described in EN 1990 for structural design and is adopted by other guidance such as FIB Model Code and DURACRETE. Reliability analysis is a statistical treatment that allows a reliability value “Beta” to be established and tested against EN requirements for reliability for different limit states and exposure conditions and consequences. (i.e. structural criticality). Further information may be found in EN 1990, Section 2 and Appendix C.
Model development of deterioration has tended to concentrate on processes influencing the corrosion of reinforcement, principally chloride-and carbonation-induced corrosion, where a great deal of research has been focused.

The general approach for predictive modelling and performance design can be summarised as follows:
- establish design service life and serviceability limit state
- establish the cases to be modelled and define the input parameters based on the assumptions, including the exposure environments and their potential severity
- undertake predictive modelling to assess durability for different design options
- use appropriate statistical treatments to define service life at the desired limit state
- use of input parameters from modelling as performance-related specification requirements for durability design.

The following useful guidance is available for performance-based durability design. Further discussion is also provided in CIRIA documentation $^3$
- Fédération Internationale du Béton (FIB) Model Code Bulletin 34 $^4$
- Concrete Society Technical Reports 61-63 $^5$

To enable a design to be successful, performance testing must include parameters or performance tests that are deemed relevant to the deterioration process they are intended to assess.

4.  **CASE STUDY**

The comprehensive and defensible design for durability of a major crossing in the Far East was required by the Client (project not disclosed). In particular was the use of probabilistic durability design techniques for the sub-structures and superstructures of the crossing, specifically, the approach outlined in FIB Model Code $^3$ was to be used to assess the risk of deterioration due to chloride ingress and reinforcement corrosion.

The crossing comprises large cable-stay bridges (in excess of 260m spans) and RC viaduct structures comprising marine piles, massive precast pile caps and post-tensioned piers, and
composite deck. Over 5km of crossing (only a fraction of the full length of the crossing) was
designed as part of the detailed design contract.

The durability design parameters required of the project were:
- Concrete durability studied and designed to FIB Model Code
- Probabilistic modelling to $P_f=5\%$ ($-B=1.65$) as opposed to FIB recommendation to $P_f=10\%$ ($-B=1.3$), recognising climatic conditions and prestige nature of the structure
- 120 year service life to major maintenance
- Serviceability Limit State (SLS): initiation of corrosion of reinforcement
- Steel structures – utilising worldwide best practice

A Concrete Durability Strategy Document was produced for the project. The document
contained the description and understanding of all deterioration processes that were likely to
be relevant to the structure, and included consideration of local climatic and environmental
loads (e.g. temperature, wind, marine conditions, tidal conditions, salinity etc). Durability
modelling also formed a major part of the Strategy Document, using input from background
environmental information, structural design considerations and constraints, and client
expectations. Chloride ingress modelling was carried out using the error-function solution of
Fick’s $2^\text{nd}$ Law$^5$.

There was also recognition of the different types of concrete construction that was likely to
be utilised for the project, affecting different parts of the structure in various exposure
conditions. The durability strategy document was therefore required to cover these various
conditions, and consequently durability options where given for precast construction (utilising
technologies such as controlled permeability formwork for enhanced durability (by adding
effective cover in the model)), and cast in situ construction (utilising integral corrosion
inhibiting admixtures, by increasing chloride threshold) along with the more simple options.
Stainless steel was also compared against more conventional carbon steel designs. The
threshold value for corrosion of Grade 316 stainless steel was assumed to be 6 times that of
carbon steel$^5$.

Table 1 presents the cases modelled for different parts of the structure that were exposed to
different exposure zones.

The strategy document utilised probabilistic modelling to provide a range of durability
design options for concrete construction, producing a suite of performance characteristics
against various minimum cover values for the concrete, and incorporating different materials
design options. Table 2 presents the principal input distributions used in the modelling.

Key parameters such as age factor for diffusion, surface chloride concentration and
chloride threshold value were defined by a combination of literature review, use of FIB
recommendations, and referral internal durability research in the region carried out by the
client, based on consensus during technical meetings with the client at the start of the
modelling process.
Table 1: Durability cases modelled for different exposure zones and concrete types.

<table>
<thead>
<tr>
<th>Option</th>
<th>Atmospheric</th>
<th>Splash Zone</th>
<th>Submerged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel only (no special measures) (CS)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Precast option: Controlled Permeability Formwork (CPF)</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Cast insitu option: Corrosion Inhibitor (15 litres/m³ Calcium Nitrite) (CI)</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Stainless steel (SS)</td>
<td>-</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Selected input distributions for the modelling

<table>
<thead>
<tr>
<th>Variable/ Input Parameter</th>
<th>Characteristic (Modal) Value</th>
<th>Distribution Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent chloride diffusion coefficient (m²/s)</td>
<td>Variable</td>
<td>Normal (coefficient of variation =30%)</td>
</tr>
<tr>
<td>Age factor</td>
<td>Atmos: 0.60</td>
<td>Pert (0.30, 0.65, 0.7)</td>
</tr>
<tr>
<td></td>
<td>Splash: 0.62</td>
<td>Pert (0.40, 0.65, 0.7)</td>
</tr>
<tr>
<td></td>
<td>Submerged: 0.63</td>
<td>Pert (0.50, 0.65, 0.7)</td>
</tr>
<tr>
<td>Temperature regression coefficient</td>
<td>4652</td>
<td>N (4800,700,3500,5500)</td>
</tr>
<tr>
<td>Surface chloride (Csn) expressed as % by mass of total cementitious content.</td>
<td>Atmospheric: 2.2</td>
<td>Pert (1, 2, 4)</td>
</tr>
<tr>
<td></td>
<td>Splash zone: 5.2</td>
<td>Pert (4, 5, 7)</td>
</tr>
<tr>
<td></td>
<td>Submerged: 2.5</td>
<td>Pert (1, 2.5, 4)</td>
</tr>
<tr>
<td>Transfer coefficient (mm)</td>
<td>8.9</td>
<td>Beta (1.894,8.745,0,1)</td>
</tr>
<tr>
<td>Chloride threshold level to corrosion initiation expressed as % by mass of total cementitious content.</td>
<td>Carbon Steel: 0.6</td>
<td>Beta (5.3, 18.4, 0.2, 2)</td>
</tr>
<tr>
<td></td>
<td>Stainless: 2.41[5]</td>
<td>Beta (5, 3.6, 0.2, 4)</td>
</tr>
</tbody>
</table>

Random sampling of input distributions was carried out for each parameter, embedded into the mechanics of the chloride ingress model. A total of 7000 sampling events were carried out on each distribution (using Latin Hypercube sampling methods – similar to Monte Carlo sampling). The outcomes of the modelling process is presented in Table 3, showing the probability of failure for a range of design options of concrete within the splash/spray zone of the marine environment. The analysis shows the range of different concrete qualities.
(measured by apparent diffusion coefficient at 56 days) available with protection measures at a range of minimum cover values to the reinforcement.

Table 3: Outcome of modelling options for a failure probability ($P_f$) (to initiation of corrosion) of 5% for concretes in the splash / spray zone for a 120 year service life.

<table>
<thead>
<tr>
<th>Minimum cover (mm)</th>
<th>Apparent chloride diffusion coefficient at 56 days ($\times 10^{-12} \text{ m}^2/\text{s}$)</th>
<th>Protection measure</th>
<th>Probability of failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.0</td>
<td>CS</td>
<td>4.7</td>
</tr>
<tr>
<td>85</td>
<td>2.0</td>
<td>CS</td>
<td>3.9</td>
</tr>
<tr>
<td>90</td>
<td>3.0</td>
<td>CS + CPF</td>
<td>5.0</td>
</tr>
<tr>
<td>85</td>
<td>2.5</td>
<td>CS + CPF</td>
<td>4.0</td>
</tr>
<tr>
<td>80</td>
<td>2.0</td>
<td>CS + CPF</td>
<td>2.5</td>
</tr>
<tr>
<td>90</td>
<td>4.0</td>
<td>CS + CI</td>
<td>4.2</td>
</tr>
<tr>
<td>80</td>
<td>3.0</td>
<td>CS + CI</td>
<td>3.6</td>
</tr>
<tr>
<td>90</td>
<td>8.0</td>
<td>SS</td>
<td>3.5</td>
</tr>
<tr>
<td>70</td>
<td>4.5</td>
<td>SS</td>
<td>3.3</td>
</tr>
<tr>
<td>55</td>
<td>3.0</td>
<td>SS</td>
<td>3.5</td>
</tr>
</tbody>
</table>

It is anticipated that most of the concretes specified for the required development of durability performance are likely to be ternary (triple) blend cement concretes. These concretes, containing for example Portland cement, ground granulated slag or flyash, and silica fume, provide an enhanced level of performance, particularly at early ages, also utilising low water /cement ratios and advanced high range superplasticising admixtures based on polycarboxylates.

Specification for the concrete contained typical clauses on submittals for materials quality, and specified a suite of concretes for durability. The number of concrete types was limited to four different types to reduce complication and promote familiarity of the mixes: three reinforced concretes and one mass concrete. Table 4 presents a summary of the concrete specification.

Testing of the concrete for durability was carefully detailed in the specification. It was specified that during mix development, laboratories should be prepared with a number of test rigs to carry out chloride migration testing to NTB443\cite{6} and NTB492\cite{7}. Correlated results of the following were to be undertaken:

- NTB 492 versus NTB443
- NTB 492 versus resistivity (two electrode method)
- NTB 492 versus water absorption (24hr immersion)

Full statistical analysis should be carried out on the relationships between the test methods, and promoted for use in compliance during concrete production. The use of TEM resistivity
and water absorption is more practical during production, and so the establishment of valid relationships were encouraged.

Table 4: Specification of high durability concrete in the splash/spray zone for 120 year service life.

<table>
<thead>
<tr>
<th>Concrete Type</th>
<th>Reinforced Concrete – Splash Zone Option 1: Carbon Steel Reinforcement</th>
<th>Reinforced Concrete – Splash Zone Option 2: Stainless Steel Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement/Combination Type</td>
<td>30-40% PFA, Portland Cement + 5-8% silica fume OR 60-75% GGBS, Portland cement + 5-8% silica fume</td>
<td></td>
</tr>
<tr>
<td>Minimum Cement Content</td>
<td>380kg/m³</td>
<td></td>
</tr>
<tr>
<td>Maximum Cement content</td>
<td>480kg/m³</td>
<td></td>
</tr>
<tr>
<td>Maximum Water/Cement Ratio</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Maximum Characteristic Accelerated Chloride Migration Coefficient at 56 days (NTB 492)</td>
<td>$3 \times 10^{-12}$ m²/s</td>
<td></td>
</tr>
<tr>
<td>Minimum Cover to Reinforcement</td>
<td>90mm</td>
<td>55mm</td>
</tr>
<tr>
<td>Other measures</td>
<td>Use of CPF or corrosion inhibitors (optional)</td>
<td>Stainless steel (PREN&gt;20)</td>
</tr>
</tbody>
</table>

Given the onerous requirement for concrete quality and additional protective measures, it was decided early on in the project that stainless steel would be used in splash/spray zone exposure zones.

REFERENCES


