Durability Design for Concrete Structures

A Review of International Building Codes

by

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Overview

- Why the interest in Global Durability & Service Life Requirements?
- What is durability and service life?
  - How do you describe it?
  - Terminology around the world
  - Standards + Codes
- Process + Findings
- Recommendations
Assess durability provisions in concrete design

Are ACI 318 provisions adequate?

What can we learn from global colleagues?

Are durability provisions being implemented successfully?
USA – Building Design

- Concrete code requirements are designed to plug into the general building codes
- ASCE 7 has loads and requirements indicating a 50 year return period
- NO GUIDANCE AVAILABLE TO ACHIEVE AND VERIFY DESIGN SERVICE LIFE
• 75 year design service life requirement
• SHRP2 project helpful but still incomplete
• No guidance as to how to get there or verify your choices
What is wrong with US concrete design?

• Codes result in “least durable structure you are legally allowed to build”
  • Repair is an $18 to $21 billion dollar (US) business

• Focus on “structural” design in education
  • Service life is not considered

• ACI 318 lacks an integrated approach to durability

• End result?
  • Service life not achieved
  • Premature repair cycle
  • Lack of sustainability
  • Negative perception
Do we know how to design this for 100 years?

- University building
  - Concrete primary structure
  - Metal/glass curtainwall cladding
  - Exterior environment: conventional Philadelphia; no marine
  - Interior environment:
    - conventional comfort, 68-72°F; 15-30% RH winter; 25-55% RH summer
- ACI 318 OK?

CVM, Temple University - Morgan Hall, Philadelphia
100 year service life for this structure?

- Residential high-rise
  - Concrete primary structure
  - Lightweight concrete exoskeleton
  - Exterior environment: conventional Miami – HOT, HUMID, MARINE
  - Interior environment: conventional comfort, 68-72°F; 25-90% RH
- ACI 318 OK?

“Undulating Exoskeleton”
Zaha Hadid, Miami
Photo courtesy of José A. Iglesias, Miami Herald, 2017
Origin of Durable Concrete Structures

• Durability – ability of a material or structure to survive in its service environment for a desired service life

• Achieved through design, construction, and operational maintenance
  • Design – strength, serviceability, durability
  • Construction – starting point to service life
  • Operational maintenance – how is structure maintained

• Service life
  • When does it end?
  • How is it defined?
Durable Concrete Structure Characteristics

- Constructed to promote drainage
- Limited number and width of cracks
- Low drying shrinkage
- Low permeability and high chloride penetration resistance
- Adequate air void system
- Suitable aggregates to prevent AAR
- Resistant to sulfate attack
- Redundant corrosion protection mechanisms
Multi-National (International) Codes/Standards

• International Codes
  • ACI 318 and 562
  • Eurocodes (EU members)
  • fib Model Code 2010
• International Standards
  • ASTM
  • EN
  • ISO
• National Codes
  • Australia
  • Canada
  • China
  • Japan – JSCE 15, 16 and 17
Overall Impressions

- Planning for durability - significant variation in practice
  - No planning (ACI 318)
  - Mandatory service life modeling

- Service life (varying definitions)
  - User defined (function of structure type)
  - Open ended (undefined)

- Design codes formats (vary widely)
  - Prescriptive
  - Performance-based
  - Hybrid

- Maintenance requirements (vary widely)
  - Not part of typical US practice (except ACI 562)
### Key Attributes of Select Codes and Standards

<table>
<thead>
<tr>
<th>Document</th>
<th>Design Service Life (excl. or ranges)</th>
<th>Modeling Requirements</th>
<th>Performance Metric Verification</th>
<th>Construction Requirements &amp; QA/QC</th>
<th>Maintenance/Repair¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI 318</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>fib MC2010</td>
<td>To be specified by user</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>EN 206</td>
<td>To be specified by user</td>
<td>No</td>
<td>N/A – verification governed by EN 1990 and EN 1991-1-1</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>AS-3600</td>
<td>40-60 years</td>
<td>No</td>
<td></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>A23.1-14/A23.2-14</td>
<td>Yes, by reference to other Canadian stds</td>
<td>Yes, for special concretes.</td>
<td>N/A</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>JSCE Guidelines for Concrete No. 15</td>
<td>To be specified by user</td>
<td>No</td>
<td>Yes</td>
<td>Included as part of JSCE Guidelines for Concrete No. 16</td>
<td>Included as part of JSCE Guidelines for Concrete No. 17</td>
</tr>
<tr>
<td>JSCE Guidelines for Concrete No. 16</td>
<td>To be specified by user</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Included as part of JSCE Guidelines for Concrete No. 17</td>
</tr>
<tr>
<td>AASHTO LRFD Design</td>
<td>75 years</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
## Select Concrete Durability Requirements

<table>
<thead>
<tr>
<th>Document</th>
<th>Prescriptive, Performance-based, or Hybrid</th>
<th>f’c</th>
<th>w/cm Ratio</th>
<th>Concrete Cover</th>
<th>Cementitious Materials Content</th>
<th>Air Content</th>
<th>Cement Type</th>
<th>Chloride Content Limits</th>
<th>Performance Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI 318</td>
<td>Prescriptive, with select provisions containing performance alternatives</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>fib MC2010</td>
<td>Hybrid—allows entirely prescriptive or entirely performance-based concrete classes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>EN 206</td>
<td>Hybrid – allows for entirely prescriptive or entirely performance-based concrete classes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>AS-3600</td>
<td>Typically prescriptive but allows for one concrete class to be entirely performance-based</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Class U concrete properties are specified by the user “to ensure durability under the particular exposure environment.”</td>
</tr>
<tr>
<td>JSCE Guidelines for Concrete No. 15</td>
<td>Performance limit states, with informative prescriptive means by which the performance requirements can be met</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>All durability requirements are performance-based.</td>
</tr>
<tr>
<td>JSCE Guidelines for Concrete No. 16</td>
<td>Performance limit states, with informative prescriptive means by which the performance requirements can be met</td>
<td>No</td>
<td>Max. 0.65</td>
<td>No</td>
<td>No</td>
<td>Limited to assume air-entrainment</td>
<td>No</td>
<td>Limited to max. 0.3 kg/m³</td>
<td>All durability requirements are performance-based, with limited max requirements.</td>
</tr>
<tr>
<td>AASHTO LRFD Design</td>
<td>Typically prescriptive, with some performance classes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, by reference to other AASHTO stds</td>
<td>Yes, by reference to other AASHTO stds</td>
<td>As specified by user</td>
</tr>
</tbody>
</table>
Durability planning as a multi-discipline process
Extensive consideration of cracking / crack width
Service life modeling as predictive tool
Requirements varying with design service life
Performance-based requirements for concrete materials
Maintenance considerations
Durability Planning

- Australia - CIA Z7/01
  - Comprehensive guide for durability planning
  - Recognizes need for integration of design details and durability

- Canada – CSA S478
  - Durability and design service life concepts addressed

- JSCE No. 15 and 16
  - Treat durability as a process with limit states and verification steps

- ISO
  - Multiple documents on durability planning with respect to service life

- ACI
  - Not covered in a comprehensive manner
Service Life Modeling

- Typically not part of codes and specifications
- United Facilities Guide Specification (UFGS–03 31 29)
  - Mandatory use
  - Proprietary software specified
- JSCE 15 and fib model code
  - Performance limit states
    - Verify chloride / carbonation levels at the end of service life
- ACI 365
  - Developing a standard procedure for service life modeling
Cracking

- **JSCE 15**
  - Crack width as function of environment and cover

<table>
<thead>
<tr>
<th>Type of reinforcement</th>
<th>Environmental conditions for reinforcement corrosion</th>
<th>Limit value of crack width $w_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Corrosive</td>
</tr>
<tr>
<td>Deformed bars and plain bars</td>
<td>0.005c</td>
<td>0.004c</td>
</tr>
<tr>
<td>Prestressing steel</td>
<td>0.004c</td>
<td>_____</td>
</tr>
</tbody>
</table>

- **ACI 318**
  - No longer directly considered
  - Reinforcement spacing limits
Design Service Life

• JSCE 15
  • Consideration given so that durability, safety, serviceability and restorability are maintained throughout design service life
  • Provisions provided for variable service life

• EN 1990
  • Select service life based upon expected use of structure

• ACI 318 and 562
  • Not directly considered
  • Loads are based upon a 50 year return period
Performance-based Concrete Requirements

- Prescriptive measures most common
  - Specified strength, $f'c$, w/c ratio, etc.
- JSCE
  - Performance-based
  - Prescriptive options
  - Service life considerations
- ACI 318
  - Prescriptive based upon exposure

From JSCE 16
• Birth to dismantlement common in international codes
  • JSCE 15 (3.2) – part of design process
  • ISO, *fib*, EN – all have repair codes

• US Practice
  • IBC (new) versus IEBC/IPMC (existing)
  • ACI 318 – not considered
  • ACI 562 – maintenance requirements
    • Very controversial
    • Inform owner
    • Protect design professional

Adapted from: Extending the Service Life of Parking Structures, Shiu, K, and Stanish, K. Concrete International V. 30 No. 4
Durability planning is not considered

Prescriptive requirements for concrete materials
  - Similar to many international codes

Lack of integrated approach to durability
  - Limited commentary on how to achieve durability
  - Reinforcement not integrated with materials
  - Limited consideration of service life and maintenance

But, do codes work?
Design Professional Interviews

• ACI 318
  • Durability design is learned “on the job” and not taught
  • Provisions are simple, limited and “cookbook”, but understanding is limited
  • Durability needs to come from codes provisions otherwise it will not occur in a cost competitive environment
  • Special inspection process is key to proper construction

• CSA A 23.1
  • Provides better flexibility than fib 2010, and better requirements than ACI 318

• JSCE
  • Majority of structures achieve acceptable durability but problems occur
  • More education on durability is needed
Design Professionals

- Experienced but not specialized
- Knowledgeable and/or specialized
- Active ACI, ICR, JCI member
- Some experience, education or training
- No experience, education or training
Improving ACI Documents

- Education of design professionals
  - Academic training
  - Continuing education
- Standardize terminology
- Integrate structural and durability design
- Develop durability planning guide
- New standards development
  - Durability design
  - Service-life prediction
- Learn from best international practices
Acknowledgements

• Pivot Engineers
  • Joseph Klein and Randall Poston – co-investigators
• ACI Foundation
  • Research sponsor
• Interview participants
Thank You

Questions?