Knowing the cause of concrete deterioration and finding the right repair solution

Ir Dr HW Pang

18 April 2012
Outline

1. Resources available
2. Investigation methodology
3. Finding the causes
4. Finding the solution

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Resources at your finger-tips

HKIE  BD  Search the web: eg, ICRI

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Buildings Department

Frequently Asked Questions - Building Maintenance

Building Maintenance Guidebook
- BY CHAPTERS
- FULL VERSION (19176KB)

An Introduction to the Co-ordinated Maintenance of Buildings Scheme

Building Safety Loan Scheme

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Knowing the cause of concrete deterioration in buildings and finding the right repair solution
ICRI PROJECT AWARDS PROGRAM

ICRI conducts an awards program each year to honor and recognize outstanding projects in the concrete repair industry. Entries are received from around the world, and the winning projects are honored each year at the annual ICRI Awards Dinner and Reception at each ICRI Fall Convention.

2012 PROJECT AWARDS

Rules and Entry Forms for the 2012 ICRI Project Awards are now available! Click on the link below.

ICRI 2012 Project Awards Forms

The 2012 Project Awards Banquet will take place at the ICRI 2012 Fall Convention at the Rancho Las Palmas Resort and Spa in Rancho Mirage, CA, on Thursday, November 8, 2012.

Photos and descriptions of the 2011 Project Award winners have been posted!
ICRI 2011 PROJECT AWARD WINNERS

2011 PROJECT OF THE YEAR

The Royal Floridian Resort is a seven-story vacation resort that is a major economic driver in the small coastal town of Ormond Beach, FL. Originally built in 1973, the building had received several alterations over the years, but the progressive deterioration caused by the harsh saltwater environment had never been addressed...

Award of Excellence
> Bellaire Tower — The Jewel of Russian Hill
High-Rise — Sika Corporation

Award of Excellence
> St. Charles Municipal Center River Wall and Plaza Restoration
Historic — Wiss, Janney, Elstner Associates, Inc.

Award of Excellence
> The Restoration of the Baha’i House of Worship
Longevity — The Armbruster Company

Award of Excellence

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Engineers should understand:

- The building structure
- The durability factors
- Defects, degradation and symptoms
- Survey, test and repair methods

Knowing the cause of concrete deterioration in buildings and finding the right repair solution.
Investigation Methodology

- Information search
- Visual inspection
- Testing
- Assessment
  - Aggressive action identification
  - Deterioration rates
  - Structural adequacy
- Developing repair solution

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Visual inspection

- Measurement
- Moisture Survey
- Taking Photo
- Tapping Test

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Open-ups, measurements and tests

1. Steel bar size and spacing
2. Concrete cover
3. Carbonation depth

Core compression test

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Chloride Content Test

1. Chloride content
2. Chloride profile

Hole drilling to extract concrete powder for chloride diagnosis
Other Tests, such as....

Infra-red Camera

Use of Florescence Solution for Seepage Detection

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Re-bar Corrosion Rate measurement

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Finding the root causes – frameworks

ISO 15686

EN1504

CSIP

Knowing the cause of concrete deterioration in buildings and finding the right repair solution

- Inherent performance level
- Design level
- Work execution level
- Indoor environment
- Outdoor environment
- Usage conditions
- Maintenance level
- Design
- Material
- Workmanship
- Environment - indoor
- Environment - outdoor
- Usage
- Maintenance

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Multitude of Causes (1)
Material, Design and Workmanship

- Piping Through Slab
- Porous infill to Squad Type Toilet
- Inadequate fall gradient
- Undesirable Drain Design

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Multitude of Causes (1) Material, Design and Workmanship

- Earlier design weak in durability
  - Lower concrete strength
  - Small cover to re-bars
  - Toilet-bathroom layout design
  - Little waterproofing
- Sea water for flushing toilet
Multitude of Causes (2)
Environment

Wet and Dry External Areas
Overflow of Salt Water

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Air-borne chloride near the sea

Findings - Chloride Profile in Wall & Slab

External

Deposition of air-borne chloride

Chloride Profile

High (0.47%)

Low (0.03%)

Internal

Open corridor

High (0.8%)

Low (0.2%)

wall

floor

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Acid Rain

Findings

• Acid rain test – pH as low as 3.7 recorded

• Reference from Hong Kong Environmental Protection Department - acid rain if pH < 5.0
  • pH value of vinegar – 2.4 to 3.4

pH of Rainwater at a Coastal Estate

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Multitude of Causes (3) Usage and Maintenance

• Low level of tenants’ care
• Low maintainability

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Finding the right repair solutions – frameworks

ISO 15686  
EN1504  
CSIP

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Principles of Repair according to EN1504

- Ingress Protection
- Moisture Control
- Restoration
- Strengthening
- Physical Resistance
- Chemical Resistance
- Restoring Passivity
- Increasing Resistivity
- Cathodic Control
- Cathodic Protection
- Anodic Control

Water and moisture

Strength

Ingress resistance

Passivity and resistivity

Electro-chemical approach

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Additional Principles based on CSIP Experience

- Increasing Maintainability
- Improving Micro-environment
- Omitting Vulnerable Elements
- Replacing Vulnerable Elements

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Increasing Maintainability

Improving Micro-environment

Omitting Vulnerable Elements

Replacing Vulnerable Elements

Inspection panel required

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Cracks along the vertical joint of the water proofing system.

Solution: remove enclosure
Improving Micro-environment

Converting grille facade walls to solid walls with windows

Increasing Maintainability

Improving Micro-environment

Omitting Vulnerable Elements

Replacing Vulnerable Elements

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Solution: lay screed with adequate fall

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Porous Plinth Material

Improving Micro-environment

Increasing Maintainability

Replacing Vulnerable Elements

Omitting Vulnerable Elements

Porous Plinth Material

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Plinth jacketing

- Increasing Maintainability
- Improving Micro-environment
- Omitting Vulnerable Elements
- Replacing Vulnerable Elements

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Loose bedding under floor tiles promotes undesirable aquaduct effect

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Protection Against Water Ingress

Past

Now

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Improving Micro-environment

Replacing Vulnerable Elements

Omitting Vulnerable Elements

Increasing Maintainability

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Improving Micro-environment

Replacing Vulnerable Elements

Increasing Maintainability

Omitting Vulnerable Elements

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Concrete Repair Strategy – People Orientated Approach

- **Shortest Time**
- **Nuisance Minimized**
- **Inconvenience Minimized**
- **Working Environment Improved**
- **Welcomed by Tenants**

High Performance Concrete Work in a day (open to tenants at night)

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Environmental Friendly Concrete Removal Method: Hydro-Scarification

(a) Jack Hammer Breaking

(b) Hydro-Scarification

Knowing the cause of concrete deterioration in buildings and finding the right repair solution...
Noise Absorbent Curtains at working areas to reduce noise and dust

Dust Screen Protection in Tenant’s Flat

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Inconvenience Minimized

Repair of toilet floor

Temporary toilet installed in tenant’s flat after day 1 work

Completion of Toilet Improvement (day 2)

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Enhanced extraction using High Efficiency Particulate Air Filter

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
Consultation with Tenants & Council Members

Partnering Workshops with Tenants

- Shortest Time
- Nuisance Minimized
- Inconvenience Minimized
- Working Environment Improved
- Welcomed by Tenants

Knowing the cause of concrete deterioration in buildings and finding the right repair solution
References

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Proceedings of the Hong Kong Standing Committee on Concrete Technology Annual Seminar, 18 Feb 2008

(2) PANG, H.W. and CHAN, C.O.
“The Comprehensive Structural Investigation of Hong Kong’s aging public Rental Buildings”
Proceedings of the 17th Congress of IABSE, Chicago USA, 17-19 September 2008

(3) PANG, H.W., and AU, Bosco, L.K.
“Sustaining public rental housing with environmental friendly repair solutions”

(4) PANG, H.W, CHAN C.O. and AU, Bosco, L.K.
“Solution – Based Approach in Structural Defect Assessment and Repair of Public Rental Buildings”
Proceedings of the Hong Kong Concrete Institute Seminar on Concrete Damage Assessments- Concrete Repair, and Concrete Mix Technology, Hong Kong, 5 Feb 2010.

(5) PANG, H.W., CHAN, C.O. and AU, Bosco, L.K.
“The Three Enables of Building Sustainability – Building Pathology, Performance Monitoring and Estate Improvement”

(6) PANG, H.W., AU, Bosco L.K.
“Advances in the Practice of Concrete Repairs – the Hong Kong Housing Authority Experience.”
Thank you for your attention
How long can a reinforced concrete building serve us?

Irv Dr HW Pang
18 April 2012
Outline

1. From a historical perspective
2. Concepts and questions on service life
3. A model of prediction of residual service life
A brief history of...

Knap of Howar
A stone house in Scotland
3500-3100 BC

The Maison Carree of France
432-447 BC

Iron Age began
1300-1200 BC

Roman concrete

Ingalls Building, Ohio, US - the first reinforced concrete high-rise building (16 storeys)
1903

1903

Cementitious materials
3000 BC

3000 BC

2012

SCCT Annual Concrete Seminar 2012 - How long can a reinforced concrete building serve us?
Knap of Howar
A stone house in Scotland

3500-3100 BC
The Maison Carree of France – the only completely preserved temple of the ancient world

432-447 BC
US bridge collapse
August 2007

How about buildings?

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Engineers learned from experience and produced better designs...

(Fib 2006): Service life relates to
- A number (of years)
- A limit state
- A probability
- A Degradation model
Published examples (1)

New city development project at Tjuvholmen, Oslo, Norway (2005)

1. Design life - 150 years
2. SLS – initiation of corrosion due to chlorides
3. Not more than 10% probability of corrosion initiation at 150 years
4. Verification by measurement of chloride diffusivity and concrete cover (results based on 28-day control 1-4%; insitu data 0.7%)

Source: Concrete International, September 2010
Published examples (2)

Design of Busan-Geoje Fixed Link, South Korea

1. Design for 100 years
2. SLS – initiation of corrosion
3. 90% probability, reliability index 1.3

Source: Proceedings of the International Conference on Concrete Repairs, Rehabilitation and Retrofitting 2006
Published examples (3)

Appraisal of 2 relatively new concrete structures (7-8 years old) in Norwegian harbours

1. Monte Carlo Simulation of variables (concrete covers, chloride diffusion coefficients)
2. SLS – initiation of corrosion
3. 90% probability, reliability index 1.3

Source: Proceedings of the 4th International Conference on Concrete under Severe Conditions of Environment and Loading, Seoul, Korea, 2004

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Published examples (4)

Design of Sitra Bridges, Bahrain

1. Design for 120 years
2. SLS – initiation of corrosion due to chlorides or carbonation
3. 90% probability of no corrosion initiation, reliability index 1.3

Source: Concrete International, September 2010
Concept of limit state and reliability

Service life has to be associated with a defined limit state: serviceability (SLS) or ultimate (ULS).

There are world-recognized levels of reliability for SLS and ULS.

References:
1. ISO 15686 (Buildings and constructed assets- service life planning) various parts 2000+
2. Fib Model Code for service life design 2006
3. Fib Model Code 2010
ISO 15686 (Buildings and constructed assets- service life planning)- Part 7- 2006 (Performance evaluation)

Limit States

Reliability

Figure B.1 — Levels of deterioration of concrete as related to performance degrees and limit states

4 spalling of the concrete cover
5 formation of cracks
6 deterioration recognizable through non-destructive measuring methods
7 depassivation of the reinforcement
8 condition can be comprehended by monitoring

Key
Y level of deterioration
X time of exposure, years
1 initiation period
2 propagation period
3 collapse of the structure through bond failure or reduction of the cross section of the load bearing reinforcement

4 Performance degrees (PD) are defined in 5.3.4.2.2.
Appropriate limit states:

1. Depassivation of rebars
2. Cracking due to rebar corrosion
3. Spalling of concrete cover
4. Collapse due to loss of rebar steel area

(SLS represents all limit states except that associated with collapse or other similar forms of structural failure)

Fib Model Code for service life design 2006
Figure R1.1-I: Deterioration process of reinforcement corrosion and definition of limit states for basic scheme of the service life design
Table 3.3-6: Suggested range of target reliability indices $\beta$ for existing structures, related to the specified reference periods.

<table>
<thead>
<tr>
<th>Limit states</th>
<th>Target reliability index $\beta$</th>
<th>Reference period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serviceability</td>
<td>1.5</td>
<td>Residual Service Life</td>
</tr>
<tr>
<td>Ultimate</td>
<td>in the range of 3.1 - 3.8*</td>
<td>50 years</td>
</tr>
</tbody>
</table>
Is there life after corrosion starts?…

Questions: will service life ends even if
• Some elements have no corrosion
• Spalling repairs can easily be done
• There is spare structural capacity
EN 1504   Products and Systems for The Protection and Repairs of Concrete Structures
ISO 15686 Buildings and Construction Assets – Service Life Planning
ISO 2394: 1998 General principles on reliability of structures
Reversible limit state

Table E.1 — Relationship between $\beta$ and $P_i$

<table>
<thead>
<tr>
<th>$P_i$</th>
<th>$10^{-1}$</th>
<th>$10^{-2}$</th>
<th>$10^{-3}$</th>
<th>$10^{-4}$</th>
<th>$10^{-5}$</th>
<th>$10^{-6}$</th>
<th>$10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>1.3</td>
<td>2.3</td>
<td>3.1</td>
<td>3.1</td>
<td>3.7</td>
<td>4.2</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table E.2 gives an example of calibration lifetime target $\beta$-values, depending on the consequences of failure and the relative cost of safe design.

Table E.2 — Target $\beta$-values (life-time, examples)

<table>
<thead>
<tr>
<th>Relative costs of safety measures</th>
<th>Consequences of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>small</td>
</tr>
<tr>
<td>High</td>
<td>A</td>
</tr>
<tr>
<td>Moderate</td>
<td>1.3</td>
</tr>
<tr>
<td>Low</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Some suggestions are:

A: for serviceability limit states, use $\beta = 0$ for reversible and $\beta = 1.5$ for irreversible limit states.

B: for fatigue limit states, use $\beta = 2.3$ to $\beta = 3.1$, depending on the possibility of inspection.

C: for ultimate limit states design, use the safety classes $\beta = 3.1$, 3.8 and 4.3.
It is perfectly acceptable to replace a ceiling light bulb,... but not every day!
Approaches to the Management and Maintenance of Structures

Relative structural performance

Proactive: Structure in good condition

Reactive: Structure in poor condition

Service “failure” criteria

Relative costs (cumulative)

Proactive

Reactive

Time

Adapted from CSTR 69:2009 Repair of Concrete Structure with ref to BS EN 1504

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Performance without preventative actions

Quality / Function

Operation and Management of Building over Time

New Requirements

Then-requirements

Repair / Refurbishment

Performance without preventative actions

Upgrading

Renewal

Performance Degree

Adapted from ISO 15686-7:2006
Performance without preventative actions

*Action now!*

Operation and Management of Building over Time

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Residual Service Life

Need for service life model for aged buildings with corrosion in propagation stage

1. Slabs and walls deteriorate differently
2. Large variability of corrosion rates
3. Difficulties in verifying the reliability of the existing structure
4. Contribution of structured inspections and maintenances
5. Slab spalling repairs: a normal maintenance task, not end of life
A new methodology - principles

**Slab corrosion**
- Reversible serviceability limit state (RSLS)
- Repair cost as acceptability of the RSLS

**Wall corrosion**
- Ultimate limit state
  - Appraisal based on measured corrosion rates and its variability
  - Structural sensitivity analysis
References

(1) PANG, H.W., CHAN, C.O. and CHAN, W.B.
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Thank you for your attention