Estimation Method on Deterioration of Marine Concrete Structures Due to Chloride Attack

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Contents

• Outline of deterioration process of marine concrete structure

• Examination of durability for marine concrete structure in durability design

• Simulation model of corrosion of reinforcement in concrete

• Evaluation of structural performance of concrete structure deteriorated due to corrosion of reinforcement
Deterioration process on marine concrete structures

Concrete (pH-12.5) -> Chloride ions -> H₂O -> Crack

Rebar -> Passive film -> Passive film destruction -> Rust (volumetric expansion) -> Delamination

Chloride-induced deterioration process
Deterioration process on marine concrete structures

Chloride-induced deterioration process
Deterioration process on marine concrete structures

Definition of stages in the deterioration process and primary factors characterizing each stage

<table>
<thead>
<tr>
<th>Stage No.</th>
<th>Definition of period</th>
<th>Primary factors characterizing the deterioration</th>
</tr>
</thead>
</table>
| I         | Period of chloride penetration until the chloride concentration around rebars up to the threshold value | • Chloride diffusion rate  
• Cover thickness                                                               |
| II        | Period of the corrosion progress on rebar until concrete cracks due to the corrosion appear | • Rebar corrosion rate  
• Resistivity against cracking of concrete                                     |
| III       | Period of the corrosion progress on rebar after appearance of concrete cracks         | • Rebar corrosion rate  
• Width of cracks due to rebar corrosion                                          |
| IV        | Period of degradation of structural performance induced by rebar corrosion and concrete cracks |                                                                           |
Deterioration process on marine concrete structures

1. **Marine environment**
2. **Chloride penetration into concrete**
3. **Passive film on reinforcement is lost**
4. **Corrosion of reinforcement starts**
   - **Water Oxygen**
   - **Reduction of Cross-section of reinforcement**
   - **Introduce of corrosion cracking and spalling of concrete**
5. **Degradation of structural performance of the structure**
Deterioration process on marine concrete structures

Penetration of chloride into concrete

In sea water, Splash zone, **Marine atmospheric Zone**

**Penetration of Cl\(^-\) via pores** to the interior of concrete

Cement hydrate binds some of Cl\(^-\) chemically

**Fredel’s salt** \((C_3A\cdot CaCl_2\cdot nH_2O)\)

Only the **free chloride diffuses** into concrete

**When critical concentration** of free Cl\(^-\) accumulates on reinforcement surface, corrosion starts on it
Chloride distribution profiles in concrete bridge beams in coastal zone after 17 years of service.
Microstructure of Cement paste

In hydration

Water

Unhydrated cement

Original particle boundary

Hydrate

Unhydrated cement

Gel pores

Capillary pores

C-S-H grains

Inner products

Unhydrated cement
Schematic representation of porosity classification in concrete

Porosity distribution

- Gel pores
- Interlayer pores: 1 Å ~ 50 nm
- Capillary pores: 10 nm ~ 50 μm
- Macro pores: 50 μm ~
- Construction pores
- Entrained air

Radius of pore (m)

- 10^{-10}
- 10^{-8}
- 10^{-6}
- 10^{-4}
- 10^{-2}
Binding of chloride ions into cement hydrate

Physically absorbed Cl$^-$

Chemically bound Cl$^-$

Chemical binding equation

$$3CaO \cdot Al_2O_3 \cdot 6H_2O + CaCl_2 + 4H_2O \rightarrow 3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$$

Fredell’s salt
Deterioration process on marine concrete structures

Penetration of chloride into concrete

Diffusion equation
(Modified Fick’s second low)

\[
\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right) - K \cdot C
\]

\(t_1 < t_2 < t_3\) : Age of structure

C: Concentration of Cl\(^-\) at depth (x,y,z) after t
D: Diffusion coefficient
K: Cl\(^-\) binding coefficient
Deterioration process on marine concrete structures

Critical chloride content

\[
\frac{[Cl^-]}{[OH^-]} \geq 0.6
\]

Effect of Chloride concentration and pH on initiation of corrosion
Deterioration process on marine concrete structures

Critical chloride content

In case of ordinary reinforcing bar in concrete

0.05% Cl\(^-\) related to the weight of Concrete

or

0.4% Cl\(^-\) related to the cement weight

or

1.2 kg/m\(^3\) of Cl\(^-\) per unit concrete volume
Deterioration process on marine concrete structures

Corrosion process on reinforcement

\[ 
\begin{align*}
\text{Cl}^{-}, & \quad \text{H}_2\text{O}, & \quad \text{O}_2 & \quad \text{Cl}^{-}, & \quad \text{H}_2\text{O}, & \quad \text{O}_2 \\
\text{Fe}^{2+} + 2(\text{OH})^- & \rightarrow \text{Fe(OH)}_2 & \quad 2\text{Fe(OH)}_2 + 2(\text{OH})^- & \rightarrow 2\text{Fe(OH)}_3 & \quad \text{H}_2\text{O} + \frac{1}{2}\text{O}_2 + e^- & \rightarrow 2(\text{OH})^- \\
\text{Fe} & \rightarrow \text{Fe}^{2+} + 2e^- & \quad & \quad & \quad & \\
\end{align*} 
\]

Corrosion current \( \propto \) Corrosion rate

Passive film (20–60A)
Deterioration process on marine concrete structures

Corrosion process on reinforcement

Electric resistance of concrete

Polarization resistance

$R_p$  $R_c$  $I_{corr}$

Corrosion current $\propto$ Corrosion rate $\propto \frac{1}{R_p}$
Deterioration process on marine concrete structures

Corrosion process on reinforcement

Corrosion weight loss of reinforcement \((W)\)

Corrosion current: \(I_{corr}\)

\[
I_{corr} = k \cdot \frac{1}{R_p}
\]

\(R_p\): Polarization resistance
\(k\): Constant \((25\text{~to~}50 \text{mV})\)

Corrosion Weight loss: \(W\)

\[
W = \frac{[Fe]}{n \cdot F} \cdot I_{corr} \cdot t
\]

\([Fe]\): Atomic weight \((55.84 \text{ g})\)
\(n\): Atomic value \((Fe: n=2)\)
\(F\): Faraday’s Constant \((96,500 \text{ A/sec})\)
Deterioration process on marine concrete structures

Corrosion crack on concrete

Tensile stress
Compressive stress

Stress distributing on concrete surface

Tensile stress distributing around steel bar

Rust: this volume is two to four times of the steel’s one

(a) Thin Cover
1.5 < \frac{(2t_p+\phi)}{\phi} \leq 3.0

(b) Thick Cover
\frac{(2t_p+\phi)}{\phi} > 3.0
Deterioration process on marine concrete structures

Relationship between corrosion amount and corrosion crack on concrete

Round Bar

- c/d=5.27
- c/d=2.38
- c/d=2.13

Deformed Bar

- c/d=3.35
- c/d=2.63
- c/d=2.13

Corrosion loss (g/cm²) vs. Corrosion crack width (mm)

**c/d**: Cover thickness/diameter of rebar
High strength concrete have smaller crack width opening than normal strength concrete for same corrosion loss.

Concrete strength also influences on the crack width opening.
Deterioration process on marine concrete structures

Conceptual figure of degradation process of performance on structure

![Graph showing stages of degradation](image)

- **Stage I**: Initial condition
- **Stage II**: Early signs of degradation
- **Stage III**: Significant degradation
- **Stage IV**: Advanced degradation

Key performances:
- **Water-proofness**
- **Aesthetics**
- **Safety for third parties**
- **Load bearing capacity**

Elapsed time vs. degradation of each performance
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in load-bearing capacity

- Singly reinforced concrete

- NSC: Mangat et al.
- NSC: Almusallam et al.
- HSC: Takewaka et al.

Strength ratio (%) vs. Corrosion Loss (gm/cm²/cm)
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in load-bearing capacity

- Flexural Failure
- Shear Failure

Corrosion Loss (gm/cm²/cm)

Strength ratio (%)

Doubly reinforced concrete with shear rebars

NSC: Umoto et al.
HSC: Takewaka et al.
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in ductility of RC beam

![Graph showing loss in ductility of RC beams with corrosion loss. The graph compares singly and doubly reinforced RC beams.](image-url)
Example of performance degradation on RC beam due to rebar corrosion

Analytical result for loss in fatigue property

- Examination results
- Analysis result in case that pitting corrosion depth is equal to (corrosion weight loss + 0.15)
Extra Costs for maintaining durability of structure during the service life

- Stage I
- Stage II
- Stage III
- Stage IV

Cost for maintaining durability vs. Deterioration

- Stage I: Cost = 1
- Stage II: Cost = 5
- Stage III: Cost = 25
- Stage IV: Cost = 125

“The law of fives” presented by De Sitter
Examination in Durability Design
What is “Durability of structure”

Qualitative performance

Resistance against deteriorating actions from surrounding environment

To keep the all of required performances on structure to their levels more than the required ones during the service life
Durability design

Design carried out to ensure that the structure can maintain its required performance (functions) during the service life under environmental actions defined by Asian concrete model code

Evaluation of long-term-performance
Examination of durability

**General principle**

All required performances for structure, such as serviceability, restorability and safety under actions in normal use, wind action and seismic action, shall be examined respectively in regard of their long-term performances in the service life.
Examination of durability

Examples of durability-limit-state

**Durability-limit-state A**: All performances maintain the initial conditions.

**Durability-limit-state B**: Though some material used in structure deteriorates, negligible decay in any performance of structure occurs.

**Durability-limit-state C**: Though some structural performance deteriorates, function of structure keep in the required condition and the damages are repairable.
Examination of durability

**Class A**
No deterioration of both structure performance and material.

**Corrosion initiation time**

**Class B**
Some deterioration on material, No deterioration of structure performance.

**Corrosion crack Generation time**
(initial period +propagation period)

**Class C**
Deterioration can occur on both performance of structure and material within allowable range.
Examination of durability

Durability-limit-state for marine concrete structures

**Durability-limit-state A:**

- All performances maintain the initial condition

\[ t_d \leq t_{cr} \]

- \( t_d \): Design service life of marine concrete structure
- \( t_{cr} \): Duration until reinforcement starts to corrode

\( t_{cr} \) is seemed to be the duration until concentration of Cl\(^-\) accumulating on reinforcement surface reaches a critical value for starting corrosion
Examination of durability

Evaluation method in durability-limit-state A

\[ \gamma \cdot \frac{C_{(c, T_d)}}{C_{lim}} \leq 1.0 \]

- \( C_{(c, T_d)} \): Chloride content at reinforcement position during service life of structure
- \( C_{lim} \): Critical chloride content
- \( \gamma \): Safety factor

This concept was introduced in the 1999 version of JSCE standard specification for design of concrete structure as the verification method of durability of concrete structure.
Simplified Fick’s second law

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}
\]

C: Concentration of Cl\(^{-}\) at depth x after t
D: Diffusion coefficient

Theoretical analysis

- In sea water or tidal zone

\[
C_{(c,Td)} = C_0 \left[ 1 - \text{erf} \left( \frac{c}{2\sqrt{D \cdot T_d}} \right) \right]
\]

here,
\[
\text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_0^s e^{-\eta^2} d\eta
\]

- In splash zone or atmospheric zone

\[
C_{(c,Td)} = 2W \left[ \sqrt{\frac{T_d}{\pi D}} \cdot \exp \left( \frac{c^2}{4DT_d} \right) - \frac{c^2}{2D} \left[ 1 - \text{erf} \left( \frac{c}{2\sqrt{D \cdot T_d}} \right) \right] \right]
\]

\(C_0\): Chloride content on concrete surface
\(D\): Chloride diffusion coefficient of concrete
\(T_d\): Design service life
\(c\): Minimum cover thickness
\(W\): Accumulated chloride amount on concrete surface during unit time
Relationship between chloride diffusion coefficient and W/C of concrete

(a) In case of OPC

\[ \log D = 4.5 (W/C)^2 + 0.14 (W/C) - 8.47 \]

(b) In case of BFSC

\[ \log D = 19.5 (W/C)^2 - 13.8 (W/C) - 5.74 \]
Durability-limit-state for marine concrete structures

**Durability-limit-state B:**

- Though some material used in structure deteriorate, negligible decay in any performance of structure occurs

\[ t_d \leq t_{cr} + t_{ck} \]

- \( t_d \): Design service life of marine concrete structure
- \( t_{cr} \): Duration until reinforcement start to corrode
- \( t_{ck} \): Period of corrosion progress on reinforcement from start of corrosion until occurrence of corrosion crack on concrete
\[ t_d = t_{cr} + t_{ck} \]

**\( t_{cr} \):** Duration until reinforcement start to corrode

\[
t_{cr} = \frac{c^2}{4D_d \cdot [\text{erf}^{-1}(1-C_d / C_0)]^2}
\]

**\( t_{ck} \):** Period of corrosion progress on reinforcement from start of corrosion until corrosion crack occurs on concrete

\[
t_{ck} = \frac{1.7\alpha_N (1+\alpha_{\phi} \cdot c)^{0.85} \cdot c \cdot \left[ \frac{1}{(W/C)_0} - 1 \right] \cdot \alpha_c}{E_h \cdot \beta_t}
\]
\[
t_{ck} = \frac{1.7\alpha_N (1 + \alpha_\phi \cdot c)^{0.85} \cdot c \cdot \left[ \frac{1}{(W/C) - 1} \right] \cdot \alpha_C}{E_h \cdot \beta_t}
\]

\(c\): Concrete cover

\(W/C\): Water to cement ratio

\(\alpha_N\): Factor for strength of concrete: \(= 0.5/(W/C)\)

\(\alpha_\phi\): Factor for diameter of rebar\((\phi)\): \(= 2/\phi\)

\(E_h\): Factor for environment: \(= 1.5\) (in sea water)

\(2.5\) (tidal zone)

\(3.5\) (splash zone, coast line)

\(2.0\) (others)

\(\beta_t\): Factor for average temperature: \(= 0.7\) (under 10\(^\circ\)C)

\(1.0\) (10 ~ 20\(^\circ\)C)

\(1.3\) (over 20\(^\circ\)C)

\(\alpha_C\): Factor for type of cement: \(= 1.0\) (OPC)

\(1.25\) (BFSC)
Relationship between minimum cover thickness and maximum W/C required for durability

Design condition
OPC, Design service life: 50 years

Durability-Limit-state A

Durability-Limit-state B
Relationship between minimum cover thickness and maximum W/C required for durability

Design condition
Blast furnace slag: 50%, Design service life: 50 years
Simulation model for deterioration of concrete structure in marine environment

To evaluate more directly the durability in actual condition by using deterioration simulating model

Simulation model
- Concrete model considering scatter of quality
- Penetration model of chloride and oxygen
- Corrosion model of reinforcement

Estimation
- Progress of corrosion of reinforcement
- Period of corrosion crack generation
Simulation model for deterioration of concrete structure in marine environment

Framework of Corrosion Simulation model

- Concrete Quality
- Oxygen Diffusion
- Chloride Diffusion
- Cracks in Concrete

Progress of Corrosion
Initiation of Corrosion
Outline of the concrete model

2 dimensional reinforced concrete model

Pore distribution in concrete
- Randomly located
- Considering W/C and RH

Aggregate distribution in concrete
- Randomly located
- Considering ITZ

Sound part
Concrete
Steel
Modified pore distribution

(by Shimomura et al)

\[ V(r) = V(r) \cdot B \cdot C \cdot r^{C-1} \cdot \exp(-Br^C) \]

\( V(r) \) : Density of pore volume

\( B, C \) : Parameters depending on W/C
**Modified relative humidity**

Relative humidity = \( \frac{\text{Water-filled pore volume}}{\text{Total pore volume}} \)
**Model of aggregate**

**Interfacial transition zone (ITZ)**

The zone with several micrometers thickness lying between aggregates and hardened cement paste matrix, which has higher porosity than the bulk cement paste.
Steel

- Wet-aggregate
- Water-filled pore
- Dry-aggregate
- Air-filled pore
Specification of a route on which chlorides reach rebar in minimum diffusion time

For each section (1 cm)

Many diffusion route

Minimum diffusion time

One specific route
Diffusion of *Free chloride* described by Modified Fick’s 2nd law

\[
\frac{\partial C_f}{\partial t} = D \frac{\partial^2 C_f}{\partial x^2} - KC_f
\]

*\(C_f\) : free chloride concentration

*\(K\) : combined coefficient
Oxygen Penetration Model

Diffusion of oxygen described by stationary state condition

\[ q = D \frac{dC}{dx} \]  (Fick’s first law)

- \( q \): Flow rate of substance
- \( C \): Concentration of substance
- \( D \): Diffusion coefficient
Cracked concrete Model

Cracks may exist by external loading, drying shrinkage etc..

Bilinear route

Crack position
Definition of effective crack length

Treat as sound concrete

Effective crack length
Relationship between effective crack and diffusion coefficient

Diffusion coefficient

1/100
1/10
1
( = in water)

infinity

Effective crack length

5 cm
3.75 cm
2.5 cm
1.25 cm
0 cm
Corrosion model - based on macrocell corrosion theory -

Specification of Anode and Cathode area

Corrosion reactions start

Steel section

Anode

Cl⁻ Concentration at rebar > tolerance
Corrosion model
Estimation of corrosion rate

Cathodic control
\[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \]

Anodic control
\[ Fe^{2-} \rightarrow Fe^{2+} + 2e^- \]
\[ 4Fe^{2-} + 8OH^- + O_2 + H_2O \rightarrow 4Fe(OH)_3 \]

The lower rate between \( i_A \) and \( i_C \) is selected as the corrosion rate at anode portion.

Change of anode area

Calculate corrosion amount
**SIMULATION RESULTS**

**Corrosion initiation time**

- W/C 40 %
- W/C 50 %
- W/C 60 %
- W/C 70 %

**RH 60%**

- the larger the cover thickness, lifetime increases clearly.
- Relative humidity is also influential parameter.
Corrosion crack generation time

**Maximum**, **Average**, **Minimum**

- Max. value
- Avg. value
- Min. value

RH 60 %

Corrosion crack generation time (years)

W/C

<table>
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<tr>
<th>RH 60 %</th>
<th>Max. value</th>
<th>Avg. value</th>
<th>Min. value</th>
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</table>
SIMULATION RESULTS

Corrosion crack generation time

- W/C 40 %
- W/C 50 %
- W/C 60 %
- W/C 70 %

RH 80%

Cover thickness (cm)

Corrosion crack generation time (years)
SIMULATION RESULTS

Initial crack model

Corrosion initiation time

Effective crack length

W/C 40%

5 cm of cover thickness

Corrosion initiation time (years)

Section number
SIMULATION RESULTS

Initial crack model

Corrosion crack generation time

W/C 40%
W/C 50%
W/C 60%
W/C 70%

5 cm cover thickness

Effective crack length (cm)

Corrosion crack generation time (years)
Example for evaluation of structural performance of deteriorated RC structure
DYNAMIC BEHAVIOR OF REINFORCED CONCRETE STRUCTURES DETERIORATED BY CORROSION OF REINFORCEMENT
some structures in the severe environmental condition may be in a deteriorated condition due to the corrosion of reinforcement

piers are relatively vulnerable to earthquake because it is suffered with a very large inertial force
Introduction

Corrosion of Reinforcement

Some pier with corrosion of reinforcement may not have the structural capacities it was designed for

Rehabilitation and Repairing is being popular

Large Earthquake

Evaluation of the dynamic behavior of the piers deteriorated by corrosion becomes necessary
Introduction

Objective

- Evaluate the dynamic properties such as, **stiffness**, **ductility** and **energy absorption** of the piers deteriorated by the corrosion of reinforcement.

- Behavior of the corroded piers against the cyclic loading which are designed by:
  - Ordinary design, using JSCE code.
  - Seismic design part of JSCE along with the verification of ductility according to JRA’s specification.
<table>
<thead>
<tr>
<th>S. No.</th>
<th>Designation</th>
<th>Design Principle</th>
<th>Axial Load</th>
<th>Corrosion Loss gm/cm²/cm</th>
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### Methodology

#### Specimen Type (Contd.)

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Methodology

Specimen Size

Ducts for post-tensioning

Duct for anchor bolt

1200 mm

1000 mm

500 mm

220 mm

220 mm

320 mm

1200 mm
Reinforcement Arrangement

Ordinary Design

6 – D 20

4 – D 20

φ 9 @200 mm

φ 9 @200 mm

12.7 mm PC Tendons

Seismic Design

6 – D 20

4 – D20

φ 9 @80 mm

φ 9 @200 mm

12.7 mm PC Tendons
Accelerated Corrosion Test

Test specimen

3.5% NaCl solution

Titanium net (cathode)

Longitudinal rebar (anode)

Test specimen

Tank

Current supplier
Hydraulic Actuator with Force Sensor

Reaction Frame

12.7 mm Tendon

Test Specimen

Anchor Bolt

Dial Gauge

Loading Test Condition
Loading Cycles

Lateral Load History

Load Control

Displacement Control

Cycle Number

Displacement (mm)
Comparison of Various Corrosion Loss

<table>
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<tr>
<th>Methodology</th>
<th>Comparison of Various Corrosion Loss</th>
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<td>0.13 gm/cm²</td>
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<tr>
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<td>0.45 gm/cm²</td>
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Results and Discussion

Load Displacement Curve

Seismic Design
No Axial Load
No Corrosion
Results and Discussion

Seismic Design
No Axial Load
0.17 gm/cm²
Corrosion loss
Results and Discussion

Load Displacement Curve

Seismic Design
No Axial Load
0.22 gm/cm²
Corrosion loss
Results and Discussion

Seismic Design
No Axial Load
0.44 gm/cm²
Corrosion loss
Results and Discussion

Strength Degradation

- **Strength (kN)**
- **Corrosion loss (gm/cm²)**

- PON
- POA
- PEN
- PEA
Results and Discussion

Strength Degradation (Contd…)

Best fit curve from experimental results

result of theoretical calculation of strength reduction due to loss of area of steel only

\[ P_c = (1 - 0.6745 \Delta w^2 - 0.2969 \Delta w)P_u \]

\[ R^2 = 0.8323 \]
Results and Discussion

Ductility Degradation

\[ \mu = \frac{\delta_u}{\delta_y} \]

- \( P_u \)
- \( P_y \)
- \( 0.8 P_u \)
- \( \delta_y \)
- \( \delta_u \)

Displacement (mm)
Results and Discussion

Ductility Degradation (Contd...)
Results and Discussion

Ductility Degradation (Contd...)

![Graph showing the relationship between ductility ratio and corrosion loss for two types of piers: Pier with ordinary design and Pier with seismic design.]

For the Pier with ordinary design, the equation is:

\[ \mu_c = (1 - 0.6208 \Delta w^2 - 1.0318 \Delta w) \mu_u \]

with a correlation coefficient of \( R^2 = 0.93 \).

For the Pier with seismic design, the equation is:

\[ \mu_c = (1 - 3.2232 \Delta w^2 - 0.2765 \Delta w) \mu_u \]

with a correlation coefficient of \( R^2 = 0.97 \).
Results and Discussion

Stiffness Degradation

\[ K = \frac{F}{D} \]
Results and Discussion

Stiffness Degradation (Contd)

![Graph showing stiffness degradation over number of loading cycles for PEN-1, PEN-2, PEN-3, and PEN-4.](image)
Results and Discussion

Stiffness Degradation (Contd…)

\[ K = a e^{-bN} \]

\[ K = 11.917e^{-0.6475N} \]

\[ R^2 = 0.9839 \]
Results and Discussion

Stiffness Degradation (Contd....)

[Graph showing the relationship between 'a' (kN/mm) and Corrosion loss (gm/cm²) for different materials: PON, POA, PEN, PEA]
Results and Discussion

Stiffness Degradation (Contd....)

![Graph showing stiffness degradation vs corrosion loss for different materials]
Results and Discussion

Energy Absorption Degradation

\[ E = \sum E_n \]

Displacement (mm)

Load (kN)
Results and Discussion

Energy Absorption Degradation

![Graph showing energy absorption degradation](image-url)
Energy Absorption Degradation (Contd…)

Results and Discussion

\[ E_c = (1-1.7952 \Delta w)E_u \]

\[ R^2 = 0.90 \]

\[ E_c = (1-2.1114 \Delta w)E_u \]

\[ R^2 = 0.82 \]

Pier with ordinary design

Pier with seismic design
Results and Discussion

Comparison of Strength and Ductility

![Graph showing comparison of strength and ductility reduction for different materials.](image-url)
Results and Discussion

Comparison of Strength and Energy Absorption

![Graph showing the comparison of strength and energy absorption reduction for different materials. The x-axis represents strength reduction in percentage, ranging from 0 to 100. The y-axis represents energy absorption reduction in percentage, ranging from -10 to 100. Different markers and lines indicate different materials: PON, POA, PEN, PEA.]
Conclusions

- Seismic performances of reinforced concrete structures are seriously affected by corrosion of reinforcement.

- Strength of the pier is slightly reduced with the small increase in corrosion loss and with further increase degradation rate of strength is larger.
Conclusions

- Small corrosion amount in reinforcement increases stiffness significantly. However, within few cycles it degrades quickly.

- With the increase in the corrosion loss of reinforcing bars, reduction rate of ductility and energy absorption of the pier is much higher than that of strength.
Final Remarks
Final remarks

Problems awaiting solutions in near future

• To complete modeling performance degradation of structure with reinforcement corrosion process
• To evaluate environmental condition more correctly
• To evaluate construction works, including compaction, curing, etc.
• To establish life cycle cost evaluation method
• To systematize maintenance
• To establish total monitoring system including predictions of both chloride penetration and corrosion of reinforcement
Thank you