An Example of Repair/Reinforcement Design for an Existing RC-girder Bridge Under Salt Damage Conditions in a Cold Region

- A method using AFRPm with PVA short-fiber-mixed shotcrete -

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ABSTRACT

The bridge in this study was constructed 30 years ago along a coastline of a cold region. Cracking and spalling of the girder concrete were observed. Field survey and material test results identified salt as the main factor behind this damage.

Some repair-measures were compared. Furthermore, it was necessary to reinforce the shear strength for the new design load to cope with larger vehicles.

To overcome these problems, we performed the comparison of some measures. In the comparison of these measures, the rough LCC was examined to reduce the amount of investment.

As a result, we proposed a new measure with AFRPm (aramid-fiber-reinforced plastic mesh) fixed by using PVA (polyvinyl-alcohol) short-fiber-mixed shotcrete.
This bridge is a simple RC girder structure, and is situated along the coastline of an area with a cold, snowy climate.

The bridge was put into service in 1973, and a surface coating (epoxy resin-impregnated glass cloth) was applied in 1992, to repair cracking and rust exudation from the girder.

However, cracking continued to progress thereafter, causing damage to the surface coating and partial spalling of the cover concrete.
Salt damage was suspected as a cause of deterioration. A variety of surveys and tests were conducted.

1. Structural dimensions and rebar arrangement
2. Mix proportion estimation

Documents related to design and mix proportions of concrete have already been lost.

Structural and rebar arrangement drawings were reproduced based on cross-sectional size measurements, radar exploration and partial chipping. W/C was estimated using the mix proportion estimation method.
3. Chloride ion content measurement

Cores were collected from the girders, and were sliced into 25-mm-thick pieces in the depth direction to measure the chloride content in each test piece.

4. Others

(carbonation depth),
(compressive strength),
(static modulus of elasticity)
Cover-concrete depth at the bottom was as large as 8 cm. Chloride ion content at the positions of main rebar was below the threshold for corrosion onset.

However, corrosion crack occurred because post-treatment of the separator was inappropriate. Furthermore, some stirrups were exposed due to insufficient covering.

Even though chloride ion infiltration was blocked by the repair (surface coating) in 1992, the re-diffusion of chloride ions remaining inside the concrete caused corrosion of the rebar and cracking of the concrete.
In addition, the infiltration of water from the slab caused the progress of corrosion and the cracking of the concrete.

As cracking also occurred on the coating surface and accelerated the infiltration of chloride ions, corrosion of the rebars progressed.
Examination of salt damage repair

Prediction of chloride ion diffusion

\[ C(x,t) = C_0 \left(1 - \text{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right) \] .......(1)

- \( C(x,t) \): chloride ion content at the depth of \( x \) (cm) and at time \( t \) (year) (kg/m³)
- \( C_0 \): chloride ion content on the concrete surface (kg/m³)
- \( D \): apparent diffusion coefficient of chloride ions (cm²/year)
- \( \text{erf} \): error function

Deterioration of the rebars was estimated by finding the chloride ion content in the concrete using Fick’s diffusion equation (Eq. 1), and ascertaining whether the chloride ion content at the position of rebar was above or below the threshold for corrosion onset.
Range of removal cross-section

It is necessary to keep the chloride ion content below the 1.2 kg/m^3 threshold concentration at the position of rebar.

It is necessary to determine the design removal depth by adding the amount of newly infiltrating chloride ions after the restoration of patching, too.

Target service life was assumed to be 100 years from the time of construction.

Since the bridge was already 30 years old, the next 70 years were taken as the remaining service life subject to the prediction of deterioration.
The removal depth was changed under these conditions to determine an appropriate range.

When the removal depth was 5 cm on the sea side, the sum of the residual chloride ion content of re-diffusion and the content predicted to infiltrate over the following 70 years was calculated to be 1.1 kg/m$^3$ (in case of AFRPm with PVA short-fiber shotcrete).

Total chloride ion content was lower than the threshold chloride concentration of 1.2 kg/m$^3$.

Accordingly, the design removal depth on the sea side was determined to be 5 cm.

However, in case of the bottom of the girder, there were many cracks due to the corrosion of rebar, so a 12cm section (up to the back of the main rebar) was removed.
Consideration of countermeasures

Strength of the stirrups and Shear load bearing capacity of the RC girder were considered insufficient from the following.

Delamination and spalling of the cover concrete were observed at the stirrup.
Corrosion and loss in the cross-sectional area of the stirrup were being accelerated by salt damage.

The strength of rebars was insufficient to cope with larger vehicles (the new live load)

Therefore, methods for shear reinforcement were examined together with repair as measures against salt damage.
FRP is suitable for repair / reinforcement of existing bridges, since it is a highly workable and anti-corrosion material.

PVA short fiber is also expected to have the performance related to hazards for third party to deal with, e.g., hazard of injury and damage to people and properties posed by cover concrete lumps falling.

In addition, PVA short-fiber mixed shotcrete (1% per volume) has ductility and is highly resistant to the penetration of chloride ions, as the diffusion coefficient becomes very small (It is about 10-20% of the general concrete) because of the compaction effect of shotcreting.
To shear-strengthen RC girders on existing bridges, we proposed a new method using AFRPm with PVA short-fiber-mixed shotcrete.

AFRPm is attached to the concrete surface after the removal of deteriorated concrete by chipping using a water jet.

The materials were applied to the girder's sides and bottom surface in a “U” shape.
Shear reinforcement of girder

AFRPm is unified with the existing concrete by wet shotcrete mixed with PVA short-fiber (L=30mm, φ = 0.66mm)

A method using AFRPm with PVA short-fiber mixed shotcrete

Construction
Calculated shear capacity afforded by reinforcement using AFRPm with PVA short-fiber mixed shotcrete for an Existing RC

\[ V_{csfF} = V_{cd} + V_{sd} + V_{fd} + V_F \]

- \( V_{csfF} \): Total shear capacity
- \( V_{cd} \): Shear capacity of concrete
- \( V_{sd} \): Increase in shear capacity afforded by stirrup (Shear reinforced rebar)
- \( V_{fd} \): Increase in shear capacity afforded by FRPm
  \[ (\alpha \cdot [Af \cdot ffu(sin \Theta_f + cos \Theta_f) / sf] \cdot z) \]
- \( V_F \): Increase in shear capacity afforded by PVA short-fiber
  \[ (2 \times b \times (z/tan \theta) \times f_v) \]
The shear strength achieved by AFRPm and PVA short-fiber have been revealed in past studies.

**Equation (1)**

**Calculated increase in shear capacity afforded by AFRPm**

\[ V_{fd} = \alpha \cdot [A_f \cdot f_{fu}(\sin \Theta_f + \cos \Theta_f) / s_f] \cdot z \]

- \( V_{fd} \): Calculated increase in shear capacity afforded by AFRPmesh
- \( \alpha \): Shear reinforcement efficiency of AFRPmesh (\( \alpha = 0.6 \))
- \( s_f \): Grid interval of mesh
- \( A_f \): Cross-sectional area per mesh chord
- \( f_{fu} \): Design tensile strength of AFRPm chord
- \( \Theta_f \): Angle between the vertical direction of the mesh chord and member axis
- \( z \): Moment arm length, \( z = d / 1.15 \)
- \( d \): Effective height

This equation 1 is based on the method of calculating shear capacity afforded by shear rebars, as in the case of FRP sheet winding reinforcement.
**Equation (2)**

**Calculated increase in shear capacity afforded by PVA short-fiber shotcrete**

\[ V_F = 2 \times b \times (z/\tan \theta) \times f_v \]

- \( V_F \): Calculated increase in shear capacity afforded by PVA short fiber
- \( b \): Short-fiber-mixed shotcrete thickness (web depth)
- \( z/\tan \theta \): Length of Moment arms
- \( f_v \): Residual tensile strength of PVA short-fiber shotcrete (in the case of UFC, design average tensile strength)
- \( \theta \): Diagonal crack angle, assumed to be 45 degrees

This equation 2 is based on the fiber part of ultra-high-strength fiber reinforced concrete (UFC), using residual tensile strength instead of design average tensile strength.
In addition, durability improvement measures are necessary in cold, snowy regions, too.

Since good-quality entrained air, which prevents frost damage, is lost during shotcreting.

However, the freeze-thaw resistance of short-fiber-mixed shotcrete can be ensured by mixing in hollow microspheres (vinyl chloride acrylonitrile, approx. 50 μm in diameter).

Results of bubble distribution measurement on placed concrete and shotcrete (Vs = 0%)

Results of bubble distribution measurement on shotcrete with changed use of mixed ratio of hollow microspheres Vs
**Examination of LCC**

Some repair/reinforcement measures were compared.

LCC of 7 cases (1 to 7) shown in this table, including re-construction with a new bridge

Countermeasures compared (Cases 1 to 7)

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<th>Case</th>
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<td><strong>Repair (durability)</strong></td>
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<td>Eliminate steel-corroding factors</td>
<td>Removal of the entire cover concrete using a water jet</td>
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<td>Removal of deteriorated sections of the cover concrete using a water jet</td>
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<td>Removal of damaged sections using a water jet</td>
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<td>Electrochemical desalination</td>
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<td>Restoration of the cross-section (patching)</td>
<td>Restoration of the entire cover concrete</td>
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<td>Restoration of damaged sections of concrete</td>
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<td>Reduce supply of steel-corroding factors</td>
<td>Short-fiber-mixed shotcrete</td>
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<td>Surface penetrants</td>
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<td>AFRP sheets + surface penetrants</td>
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<td>Epoxy-coated reinforcing steel bars</td>
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<td>Control of steel-corroding</td>
<td>Cathodic protection</td>
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<td>Reinforcement (load bearing capacity)</td>
<td>AFRP sheet</td>
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<td>Shear strengthening</td>
<td>Shear rebar</td>
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<td>AFRPm + PVA short-fiber-mixed shotcrete</td>
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<td>Re-construction with a new bridge</td>
<td>Pretensioned hollow girder (salt damage-resistant type)</td>
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Examination of LCC

Costs are rough estimates of LCC including initial construction and maintenance/management expenses. e.g.,

Case 2: recoating of concrete (7.4 million yen/15 years)

Case 5: electricity charges for the cathodic protection (12 thousand yen/year), inspection costs (100 thousand yen/2 years), piping/wiring repair costs (5 million yen/20 years), not including anode exchange.

Comparison of LCC for Countermeasures

Roughly estimated LCC (millions of yen)
Examination of LCC

In addition to LCC, vehicle traffic regulations during construction were also taken into consideration.

e.g.,
Cases 1 to 5 and 7: no traffic regulations
Case 6: one-lane alternate traffic

As a result, the use of AFRPm with PVA short-fiber-mixed shotcrete (Case 7) was selected as the lowest LCC and the one with the least impact on traffic.
Conclusion

Cost reduction was realized through durability design based on the prediction of deterioration and the examination of LCC, as well as through the use of new materials and technologies as repair/reinforcement measures to enable the efficient use of existing stock.

It is considered important to further improve the accuracy of LCC and deterioration prediction.
Thank you very much for your kind attention
### Material Properties

<table>
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<tr>
<th>Grid interval (mm)</th>
<th>Guaranteed strength (Mpa)</th>
<th>Elastic modulus (Gpa)</th>
<th>Tensile strength (GPa)</th>
<th>Ultimate strain (%)</th>
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<tbody>
<tr>
<td>50</td>
<td>300</td>
<td>118</td>
<td>2.06</td>
<td>1.75</td>
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</tbody>
</table>

- **AFRPm** -