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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 RC-girder bridge in this study was constructed approximately 30 years ago and put into service along the coastline in a cold region. Cracking and spalling of the main girder concrete and other damage were observed. Since field survey and material test results identified salt as the main factor behind this damage, deterioration as a result of salt action was predicted, and different repair measures were compared. Furthermore, the shear strength of the main girder was also found to be insufficient when the design live load was reviewed to cope with larger vehicles. Accordingly, the required level of strength was ensured by adopting a method using AFRPm (aramid fiber reinforced plastic mesh) with PVA (polyvinyl-alcohol) short-fiber-mixed shotcrete to achieve both repair and reinforcement. In the comparison of these methods, the LCC (life-cycle cost) was examined to reduce the amount of investment involved.

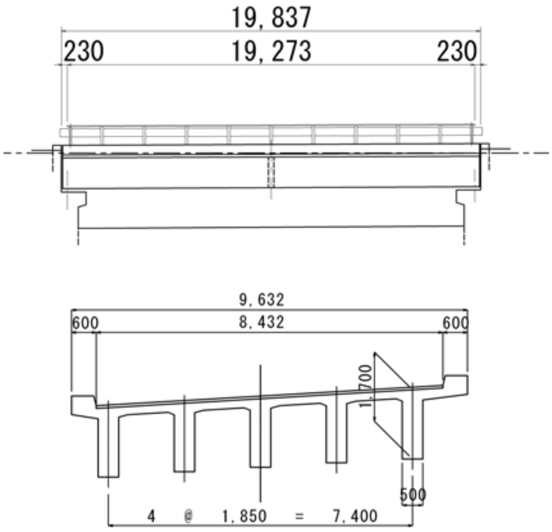
1 INTRODUCTION

This bridge is an RC-girder structure on a national highway along the Sea of Japan coast in Hokkaido (the northernmost prefecture of Japan, Fig. 1). It is a simple girder bridge of 20 m in length (Fig. 2), and is situated about 25 m from the coastline. The surrounding conditions are severe due to sea water from waves and airborne salt to the RC girder, in addition to the area's cold, snowy climate.

The bridge was put into service in 1973, and a surface coating (epoxy resin-impregnated glass cloth) was applied in 1992, 20 years after its construction, to repair cracking and rust exudation from the main girder (Photo 1). However, cracking continued to progress thereafter, causing damage to the surface coating and partial spalling of the cover concrete by 2002 (ten years after the repair).

A detailed survey was therefore conducted on the concrete, and further repair/reinforcement measures were taken.

Figure 1: Location of the bridge



Ocean side Mountain side

Figure 2: General view of the bridge

Photo 1: Damage to the main girder

2 SURVEY OF THE DETERIORATION AND DAMAGE CONDITIONS

2.1 Survey Purposes and Items

Since salt damage was suspected as a cause of deterioration, it was presumed that losses in the steel cross-sectional area occurred due to the infiltration, accumulation and diffusion of chloride ions inside the concrete and the progress of reinforcement corrosion. A variety of surveys and tests were conducted to evaluate durability.

(1) Structural dimensions and rebar arrangement

Since the design documents have already been lost, structural and rebar arrangement drawings were reproduced based on cross-sectional size measurements, radar exploration and partial chipping. Specifications and other available information from the time of design were also used as references.

(2) Chloride ion content measurement

Cores (10 cm in diameter) were collected from the main girders, and were sliced into 25-mm-thick pieces in the depth direction to enable measurement of the chloride content in each test piece.

(3) Mix proportion estimation

Since basic documents related to mix proportions of concrete have also been lost, the water cement ratio was estimated using the mix proportion estimation method of the Japan Cement Association, and the diffusion coefficient of chloride ions necessary for the prediction of deterioration was determined from the known relationship between the water cement ratio and the diffusion coefficient of ions.

(4) Other tests

Other tests were conducted to investigate the carbonation depth and the compressive strength and static modulus of elasticity to determine the degree of deterioration in the structure's material properties.

2.2 Chloride Ion Content Test Results

Figure 3 shows the results of the chloride ion content. The curves showing the chloride content are seen to rise at a depth of approximately 4 cm. This was probably because of the progress of rediffusion of the chloride ions included inside, even though the external chloride ion supply was blocked by the coating applied approximately 20 years after construction. The chloride ion contents at the position of rebars were below the threshold chloride ion content for corrosion onset (1.2 kg/m^3) except in one section.

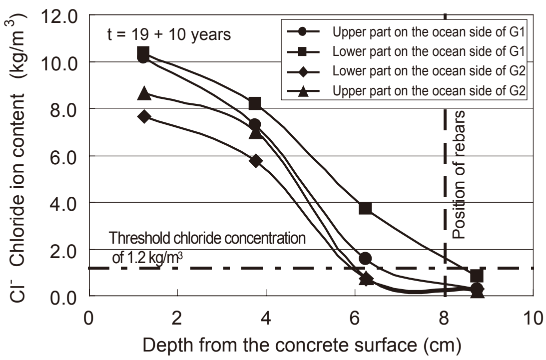


Figure 3: Chloride ion content on the ocean side of the main girder

3 ESTIMATION OF THE CAUSES OF DETERIORATION

Corrosion of rebars and cracking of concrete were estimated to be as follows:

1) For the rebars at the bottom of the main girder, the covering depth was as large as 8 cm, and the chloride ion content at the positions of rebars was below the threshold chloride ion content for corrosion onset.

2) Because the post-treatment of the separator used for the form at the time of construction was inappropriate, corrosion amount increased and

corrosion crack occurred (Photo 1). A photo taken at the time of the initial repair also showed exposure of the rebars due to insufficient covering, as well as corrosion amount increase and corrosion crack at some stirrups.

3) Even though chloride ion infiltration was blocked by the repair in 1992 (involving the coating of the concrete surface), the rediffusion of chloride ions remaining inside the concrete and the infiltration of water from the top of the bridge caused the progress of corrosion in the rebars and led to the cracking of the concrete. As cracking also occurred on the coating surface (Photo 2) and accelerated the infiltration of chloride ions, corrosion of the rebars progressed at an accelerated rate.

Photo 2: Corrosion induced cracking

4 CONSIDERATION OF COUNTERMEASURES

Since delaminination and spalling of the cover concrete were observed at the positions of stirrups and salt damage was seen to cause progress in the corrosion of the rebars and losses in the cross-sectional area, the strength of the rebars was considered insufficient.

In addition, the load bearing capacity of the RC girder to cope with larger vehicles (the new live load) was examined by considering the amount of rebars estimated from radar exploration, the restored design of the main-girder cross section and other data. The results revealed that, although the bending strength was sufficient, the level of shear strength was insufficient. Accordingly, methods for shear reinforcement were examined together with repair as measures against salt damage.

4.1 Examination of LCC

The seven cases of LCC (1 to 7) shown in Table 1, including re-construction with a new bridge, were compared.

Table 1: Countermeasures compared (Cases 1 to 7)

		Case	1	2	3	4	5	6	7
Repair (durability)	Eliminate steel-corroding factors	Removal of the entire cover concrete using a water jet	○	○					
		Removal of deteriorated sections of the cover concrete using a water jet			○				○
		Removal of damaged sections using a water jet				○	○		
		Electrochemical desalination				○			
	Restoration of the cross-section (patching)	Restoration of the entire cover concrete	○	○					
		Restoration of deteriorated sections of cover concrete			○				
		Restoration of damaged sections of concrete				○	○		
		Short-fiber-mixed shotcrete							○
	Reduce supply of steel-corroding factors	Surface penetrants	○						
		Surface coating		○					
		AFRP sheets + surface penetrants			○	○	○		
		Epoxy-coated reinforcing steel bars							
	Control of steel-corroding	Cathodic protection					○		
Reinforcement (load bearing capacity)	Shear strengthening	AFRP sheet			○	○	○		
		Shear rebar	○	○					
		AFRPm + PVA short-fiber-mixed shotcrete							○
Re-construction with a new bridge		Pretensioned hollow girder (salt damage-resistant type)						○	

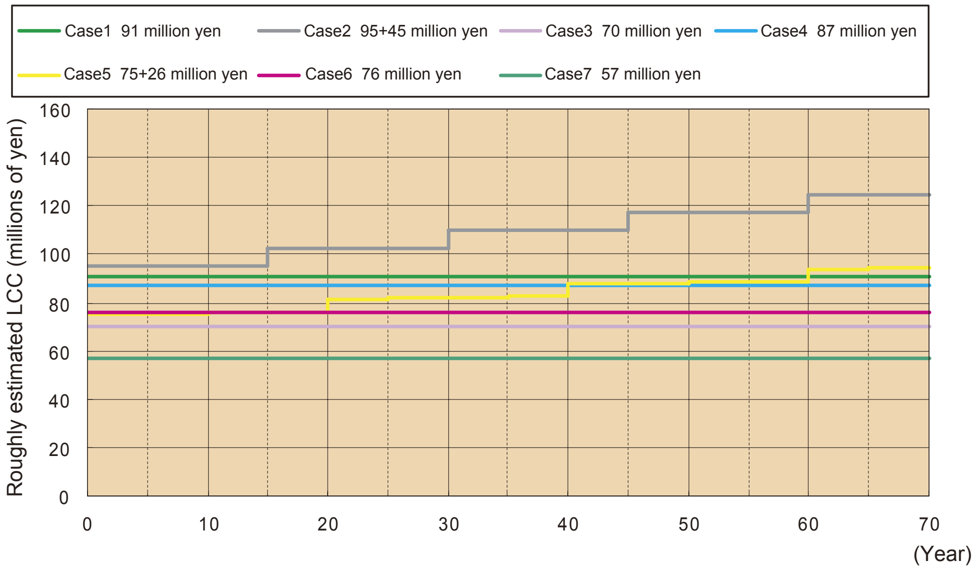


Figure 4: Comparison of LCC for Countermeasure

These costs are rough figures that include 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). In addition to LCC, vehicle traffic regulations during construction (e.g., no traffic regulations in Cases 1 to 5 and 7, one-lane alternate traffic in Case 6) were also taken into consideration.

As a result, the use of AFRPm with PVA short-fiber-mixed shotcrete (Case 7 in Fig. 4) was selected as the method with the lowest LCC and a few influences in the traffic.

4.2 Examination of Salt Damage Repair

(1) Prediction of chloride ion diffusion

The 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 rebars was above or below the threshold chloride ion content for corrosion onset.

$$C(x,t) = Co(1 - erf(x/2\sqrt{Dt})) \qquad (1)$$

$C(x,t)$: chloride ion content at the depth of x (cm) and at time t (year) (kg/m^3)
Co: chloride ion content on the concrete surface (kg/m^3)
D: apparent diffusion coefficient of chloride ions (cm^2/year)
erf: error function

(2) Range of removal cross-section

Chloride ion content on the main girder concrete infiltrate and diffuse inward with the passage of time. It is therefore necessary to keep the chloride ion content at the position of rebars at below 1.2 kg/m^3 of threshold chloride concentration. In surface covered concrete removal, harmful parts were removed as outlined below.

Since there were many cracks in the cover concrete at the bottom of the main girder due to the corrosion of rebars, a 120-mm section up to the back of the main rebars was removed.

In the case of surface coating or similar methods are adopted for the sides of a main girder:
1) Chloride ions content inside rediffuse and gradually become uniform due to the content gradient in the cross section (Fig. 5), if the external chloride ion supply is blocked; the effect of rediffusion must therefore be taken into account when determining the range of cross-section removal (removal depth).

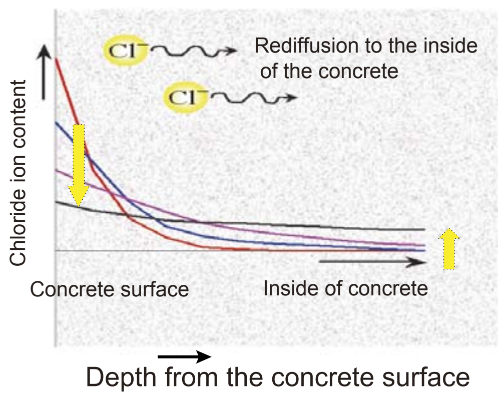


Figure 5: Uniformization of chloride ion content by rediffusion

2) It is necessary to determine the design removal depth by adding the amount of newly infiltrating chloride ions after the restoration of the cross section in the above range of removal (patching).
3) Since the target service life was assumed to be 100 years from the time of construction and 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 in which the chloride ion content at the position of rebars is within the applicable limit and durability against salt damage can be ensured.

When the removal depth was assumed to be approximately 5 cm on the ocean side, the residual chloride ion content that became uniform as a result of rediffusion was 0.82 kg/m^3. The content of the amount predicted to infiltrate over the following 70 years was estimated to be 0.24 kg/m^3. By adding these amounts together, the chloride ion content at the position of rebars was estimated to be 1.1 kg/m^3, which was lower than the threshold chloride concentration of 1.2 kg/m^3. Accordingly, the design removal depth on the ocean side was determined to be 5 cm, while that on the mountain side was determined to be 4 cm using the same method.

4.3 Shear Reinforcement of the Main Girder

In the method adopted as a new technology using AFRPm with PVA short-fiber mixed shotcrete[1], this type of mesh processed into a grid pattern (Fig. 6) is attached to the concrete surface after the removal of deteriorated concrete by chipping (e.g., using a water jet), and is unified with the existing concrete by wet shotcrete (Photo 3) mixed with PVA (polyvinyl-alcohol) short-fiber (L = 30 mm, Φ = 0.66 mm, Photo 4) (Fig. 7).

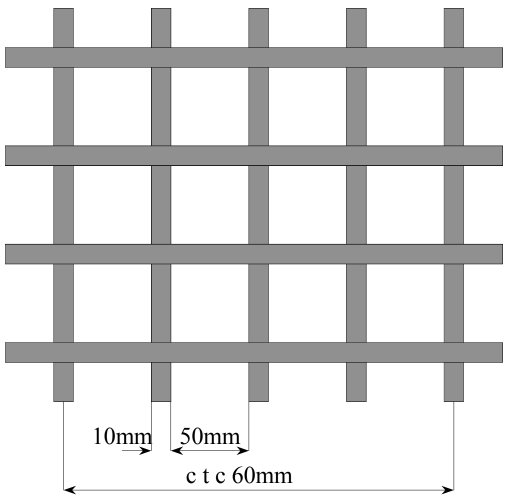


Figure 6: AFRPm

Photo 3: Construction

Photo 4: PVA short fiber

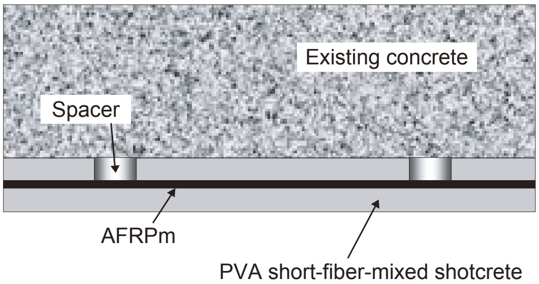


Figure 7: A method using AFRPm with PVA short-fiber mixed shotcrete

FRP is suitable for repair and reinforcement of existing bridges in areas subject to salt damage, since it is a highly workable and anti-corrosion material.

In addition, it has been confirmed through various experiments that 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 because of the compaction effect of shotcreting. 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 from shotcrete above.

In addition, it has been revealed in past studies that the shear strength achieved by AFRPm and PVA short-fiber in addition to that of ordinary RC beams can be calculated by Fig. 8 / Eq. 2 and Fig. 9 / Eq. 3 below.

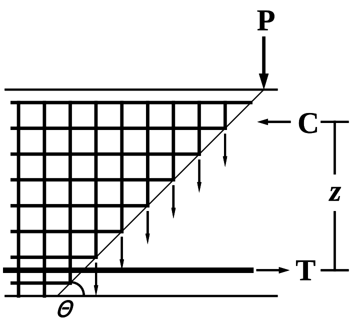


Figure 8: Shear reinforcement effect afforded by AFRPm

$$V_{fd} = \alpha \, [A_f f_{fu} \, (sin\theta_f + cos\theta_f)/s_f] \, z \tag{2}$$

V_{fd}: shear reinforcement effect afforded by AFRP mesh;
α: shear reinforcement efficiency of AFRP mesh (it is assumed that shear reinforcement efficiency is 0.6) ;
s_f: grid interval of mesh;
A_f: cross-sectional area per mesh cord;
f_{fu}: design tensile strength of AFRP mesh cord;
f_v: residual tensile strength of PVA short-fiber shotcrete (in the case of UFC, design average tensile strength) ;
θ_f: angle between the vertical direction of the mesh cord and the material axis;
z: moment arm length (= d/1.15) ;
d: effective height.

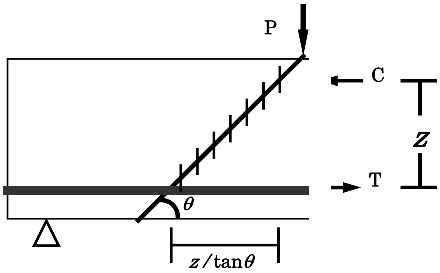


Figure 9: Shear reinforcement effect afforded by PVA short-fiber

$$V_F = 2 \times b \times (z/tan\theta) \times f_v \tag{3}$$

V_F: shear reinforcement effect afforded by PVA short-fiber shotcrete;
b: short-fiber-mixed shotcrete thickness (web depth);
θ: diagonal crack angle (assumed to be 45 degrees).

While it is necessary to implement durability improvement measures against frost damage peculiar to cold, snowy regions since good-quality entrained air is lost during shotcreting, it has also been found in past studies[2] that the freeze-thaw resistance of short-fiber-mixed shotcrete can be ensured by mixing in hollow microspheres (Photo 5, vinyl chloride acrylonitrile, approx. 50 µm in diameter) equivalent to 3% of the concrete volume.

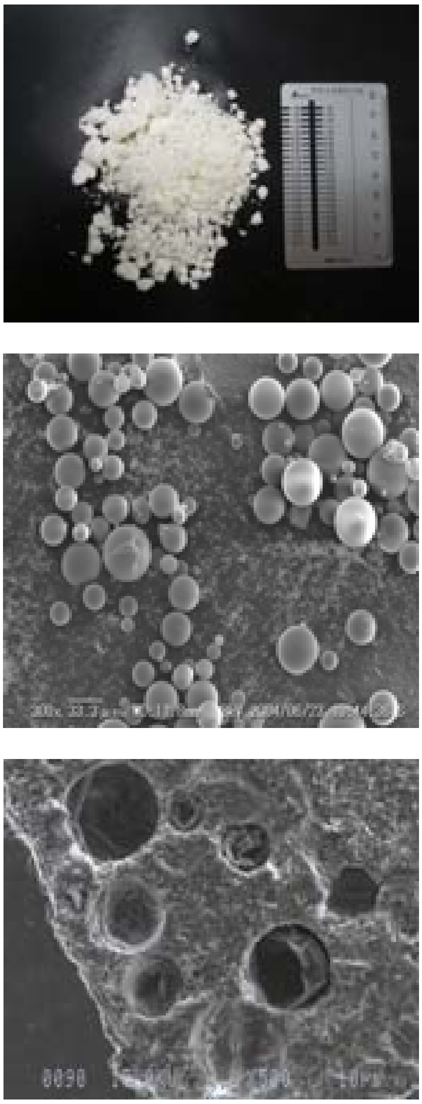


Photo 5: Hollow microspheres (in concrete)

5 CONCLUSION

Cost reduction was realized through durability design based on the examination of LCC and the prediction of deterioration, 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 in the future.

REFERENCES

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[2] F.Taguchi;Doctoral thesis, An Experimental Study on Strengthening Reinforced Concrete Members by Applying Aramid-fiber-reinforced Plastic Mesh and Shotcrete Mixed with Polyvinyl Alcohol Short Fiber, pp.1-175(2008).