

A feature of corrosion and its evaluation around the cross section of weathering steel bridge

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ABSTRACT: The bridges by weathering steel which can abbreviate painting were widely adopted in Japan to reduce LCC (Life Cycle Cost). However it is reported that some part of bridge cross-section is severely rusted by the effects of various environmental factors although most part of bridge cross-section is mildly rusted. This paper discussed the effect of environmental factors to the rust distribution of bridge section by using observed data for one year in an unpainted weathering steel bridge in Niigata prefecture such as the distribution of airborne salt and its wash-down by rainfall. Furthermore, a new approach method to evaluate partial corrosion level is proposed in this paper.

1 INTRODUCTION

Life cycle cost including the cost for maintenance is important factor, and corrosion resistance is one of important factors for steel bridges to have a long life when steel bridges are constructed in Japan. To prevent corrosion, usually painting is applied to steel bridges. Painting is effective, but costly because it occupies 5% to 15% of the initial total cost of superstructures. Furthermore repainting is required every several decades. On the other hand, bridges with unpainted weathering steel are increasingly made because it is able to reduce the initial painting and repainting costs. Under appropriate corrosive environment, atmospheric corrosion resistance is demonstrated by exposure of weathering steel.

However, in marine coastal areas with frequent high rainfall, high humidity or persistent fog, weathering steel cannot have the sufficient corrosion resistance. Rust progress is different in each part of the bridge. In strong corrosive environment, this tendency appears clearly because corrosion conditions such as the amount of airborne salt, rainfall and humidity are different in each part of the bridge. Corrosion factors such as airborne salt, humidity or time of wetness at planning location for construction of bridge can be known by observation of nature. However, the amount of airborne salt, humidity or time of wetness is influenced by direction of the bridge, clearance under the bridge and so on. Thus, the corrosion environment will be clearly after the bridge is constructed.

In this paper the influence of environmental factors on the rust distribution of the bridge section is discussed by using observed data for one year in a two-girder bridge. These environmental factors are the distribution of airborne salt and its wash-down by rainfall. Furthermore, a new approach method to evaluate partial corrosion level is proposed in this paper.

2 APPLICATION STANDARD OF WEATHWERING STEEL TO BRIDGE IN JAPAN

Weathering steel is containing small amounts of Cu, Cr and Ni to a low alloy normal steel. This steel generates protective and adhesive rust on steel surface, and suppresses further generation of rust to sufficiently low level. The application of weathering steel to bridges began in the 1960s in Japan. The ratio of weathering steel to whole steel weight of bridges has increased year by year to exceed 25% at present as shown in Figure 1.

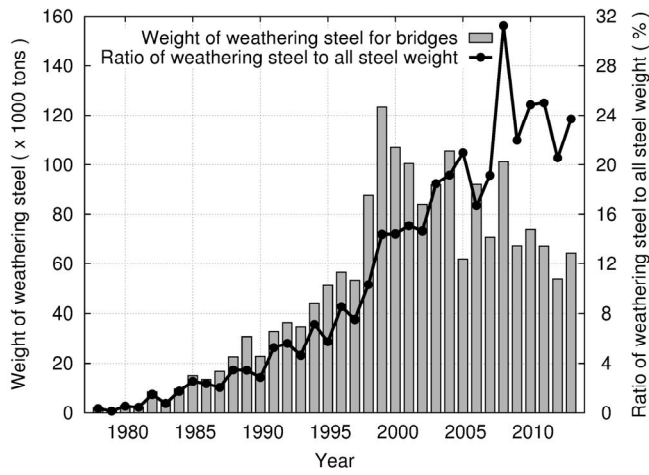


Figure 1. Progress of the use of weathering steel to bridge

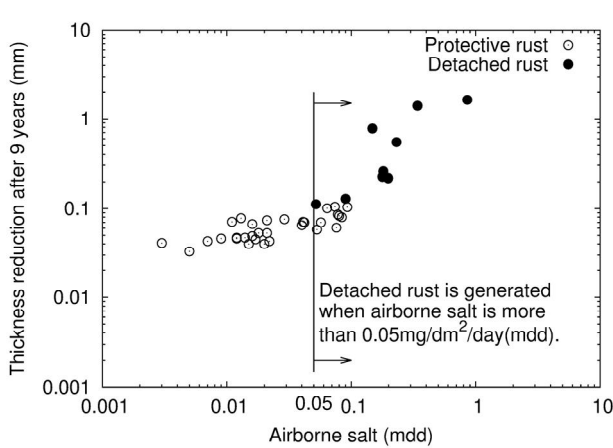


Figure 2. Relation between airborne salt and thickness reduction in 9 years by field exposure test

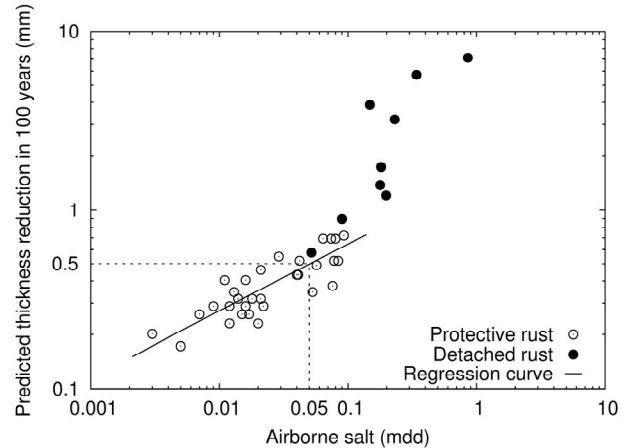


Figure 3. Predicted thickness reduction in 100 years

However, in coastal area the protective rust cannot be generated, in consequence, layered and detached rust will be obtained. The Joint Research Report XVIII on Application of Weathering Steel to Bridges (2003) was carried out over 9 years from 1981 by Public Works Research Institute of the Ministry of Construction, Kozai Club and Japan Bridge Association. This report is shown that layered and detached rust will not be seen and precise protective rust will generate if airborne salt is below 0.05 mdd ($\text{mg}/\text{dm}^2/\text{day}$) as shown in Figure 2 by field exposure test in 9 years. Furthermore, this report is shown that predicted thickness reduction in 100 years is less than 0.05 mm if the airborne salt is less than 0.05 mdd as shown in Figure 3.

The Joint Research Report (2003) shows the application standard of weathering steel to bridges in Japan. However, this standard does not consider the difference of corrosion situation in each part of the bridge. Local environment for corrosion depends on the flow of wind which includes airborne salt. The corrosion situation inside of girder cannot be observed until the bridge is built because wind flow is changed after construction of the bridge.

3 CORROSION CHARACTERISTIC OF BRIDGE

3.1 Requirement for Monitoring

Purpose of this paper is to make clear the relation between airborne salt and rust on each part of bridge section. However, the amount of airborne salt depends on direction and velocity of wind. Furthermore corrosion is affected by airborne salt, temperature and humidity and so on. Therefore, in this paper, monitoring for wind velocity, wind direction, airborne salt and quantity of thickness reduction used by test piece in one year are enforced. The monitoring bridge that satisfies following conditions is used.

(a) Conditions for environment

- i. Much airborne salt is supplied from sea.
- ii. Flying direction of airborne salt is roughly same prevailing wind direction.

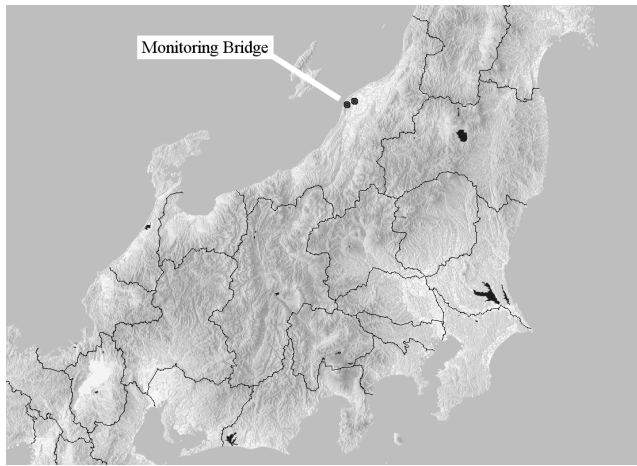


Figure 4. Location of the monitoring bridge



Photo 1. Overview of the bridge

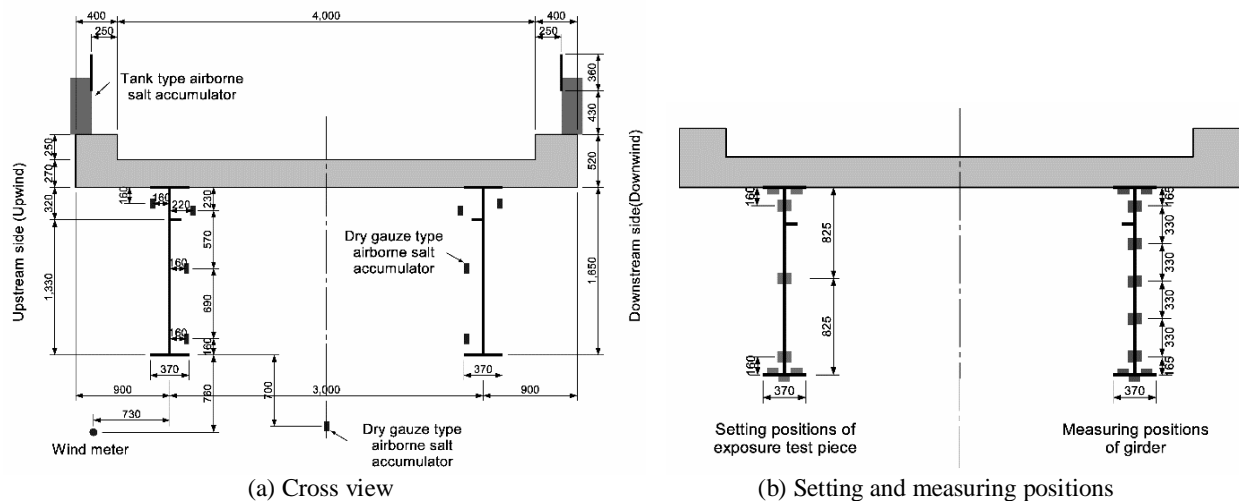


Figure 5. Structural dimensions, setting and measuring position in the bridge (Unit: mm)

- iii. There aren't barriers such as buildings, groves and plants that disturb wind flows.
- iv. De-icing salts and sulfur oxide are little, and airborne salt is main factor for corrosion.
- v. Conditions for bridge
- vi. Bridge is served over ten years, and clear difference of rust in each position has been occurred.
- vii. Prevailing wind direction is perpendicular to the bridge.
- viii. Shape of section does not vary at any position, and bridge is not skew.

An unpainted weathering steel bridge that satisfies above conditions is used for monitoring bridge. The influence of the relation between bridge direction and prevailing wind direction on corrosion is investigated by this bridge.

3.2 Outline of the Bridge

The monitoring bridge made weathering steel near the Sea of Japan in Niigata prefecture is used as shown in Figure 4, and overview of this bridge is shown in Photo 1. Around this bridge is a paddy field, and this bridge is used by agricultural motors only, therefore de-icing salts do not spread on this bridge in winter. Seasonal wind with airborne salt flow from the northwest. Direction of this wind is perpendicular in direction of the bridge. Structural dimensions of the bridge are shown in Figure 5. In this figure, setting positions of wind meter, airborne salt accumulator and exposure test pieces and measuring position of thickness of rust in girder are also shown.

3.3 Distribution of Rust Thickness in the Bridge

Figure 6 shows distribution of rust thickness at points of web, upper and lower flanges on each girder of the bridge. The rust thickness is measured by magnetic film thickness meter. In the figure, average and standard deviations are indicated at each point. By these figures, it was noted that rust thickness is large in windy part of girder surface.

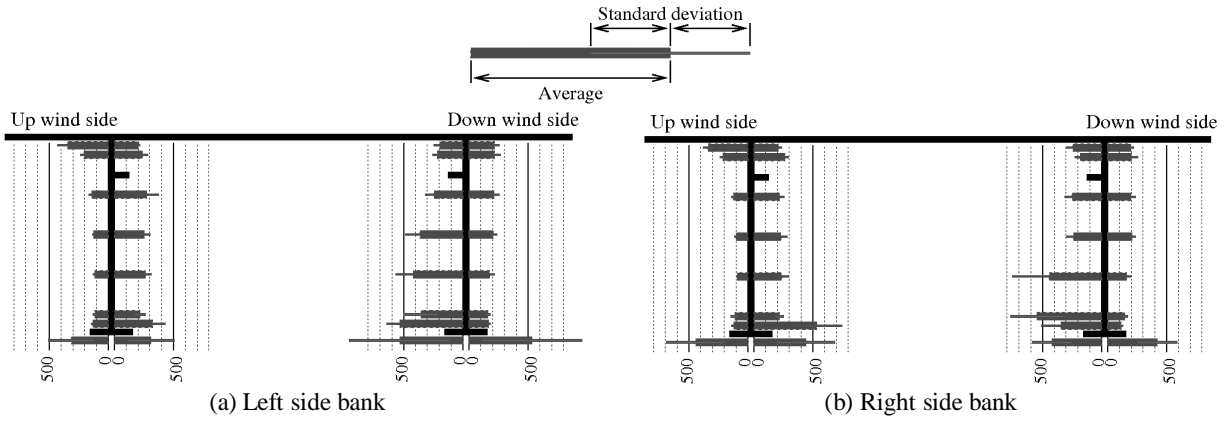


Figure 6. Distribution of rust thickness at points of web, upper and lower flanges on each girders

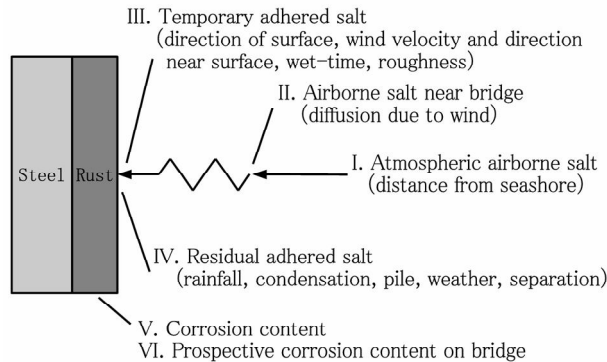


Figure 7. Corrosion and adhered airborne salt

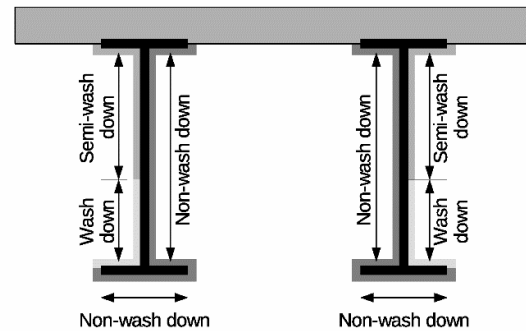


Figure 8. Wash, semi wash and non-wash down parts

4 EFFECT OF AIRBORNE SALT ON THE CORROSION

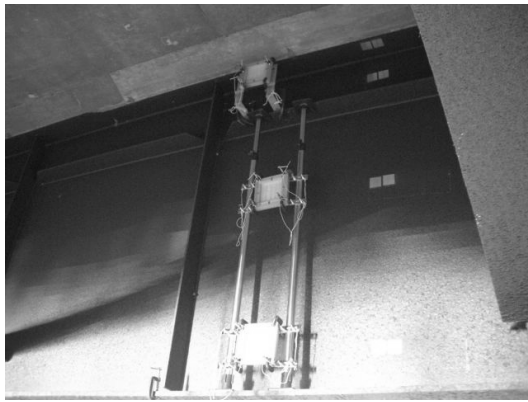
4.1 Corrosion and Adhered Airborne Salt

Corrosion occurs when airborne salt that is carried by the wind from sea; adhere to the surface of girder. This process is governed by complicated phenomena. These phenomena are conceptually classified as shown in Figure 7. Thus, these phenomena are as follows: I. Airborne salt is influence by distance from seashore and geographical features of the nearby bridge. II. Airborne salt of nearby bridge is diffused due to wind. III. Airborne salt is temporarily adhered to steel surface, and it is influenced by direction of steel surface, wind velocity, wind direction, wet-time near steel surface and roughness of steel surface. IV. Adhered salt is redistributed by rainfall, condensation, pile, weather and separation. V. Corrosion is generated due to above phenomena. VI. Future amount of corrosion will have estimated.

In lower part of web and upper side of lower flange, adhered salt will be wash down by rainfall. Raindrops hitting the upper part of web are less than lower part of web. Therefore, we think that upper part of web is semi-wash down part. Furthermore, Inside of girder is non-wash down part because of surface of inside girder is not exposed to raindrop.

4.2 Airborne Salt around the Bridge Section

To observe airborne salt around the bridge section for the monitoring bridge that corresponds to II in Figure 7, tank type and dry gauze type airborne salt accumulators are used. In these accumulators, airborne salt is measured by adhered salt on steel surface of tank and adhered salt in gauze respectively, and area of steel surface and gauze is 100cm^2 respectively. Setting conditions of these airborne salt accumulators are shown in Photo 2.

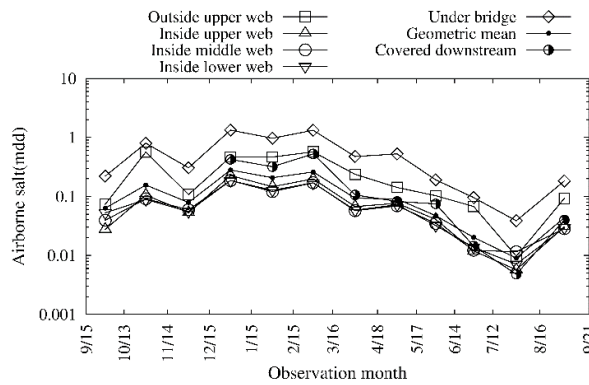


(a) Accumulator near the girder

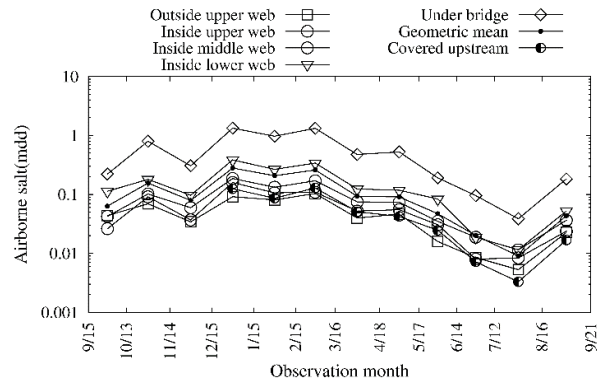


(b) Accumulator under the bridge

Photo 2. Setting conditions of airborne salt accumulators

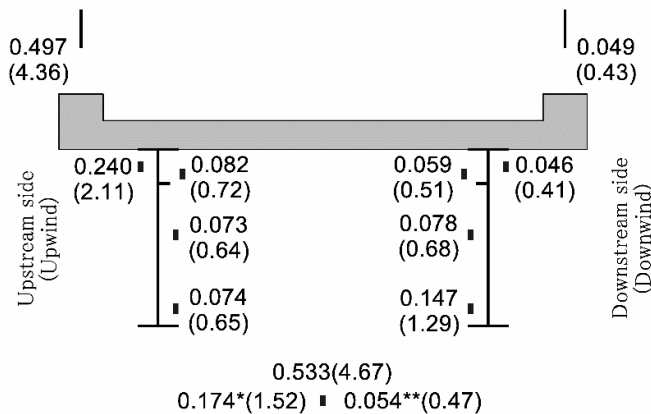


(a) Upstream side girder and under bridge



(b) Downstream side girder and under bridge

Figure 9. Airborne salt of the monitoring bridge of each month



Value inside parentheses indicates the ratio of geometric mean.

* Value is measured by accumulator that covered surface of downstream side.

** Value is measured by accumulator that covered surface of upstream side.

Figure 10. Airborne salt of the annual average near bridge section (unit: mdd)

Observation starting from September 2006 was continued one year, and accumulators monthly were exchanged. Portion of measuring results of each month are shown in Figure 9. In these figures, geometric mean of results of all positions is indicated. Figure 10 indicates an annual average of airborne salt. A unit of airborne salt is indicated by mdd that means $\text{mg}/\text{day}/\text{dcm}^2$.

Shapes of these curves of airborne salt are almost same in logarithmic graph. Therefore, airborne salt of each part in the bridge have same ratio in any month. This result means that an airborne salt at anywhere in girder can be estimated by an airborne salt as other position if the ratio of airborne salt as anywhere to other position is clearly. Ratios of airborne salt at each position based on the airborne salt of geometric mean of all positions are indicated in parentheses in Figure 10 as an example.

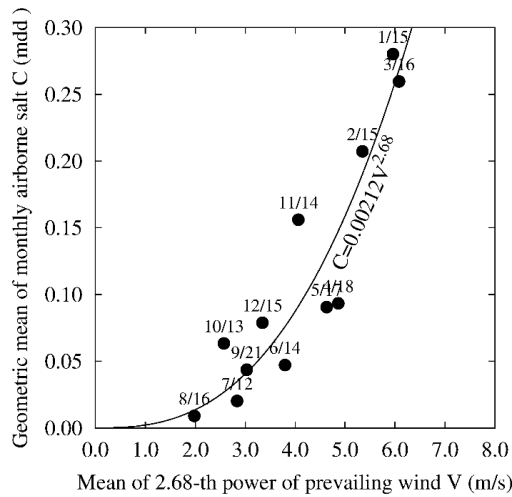


Figure 11. Relation between mean of 2.68-th power of prevailing wind velocity and geometric mean of monthly airborne salt, upper value of circular mark indicates exchanged date of accumulators

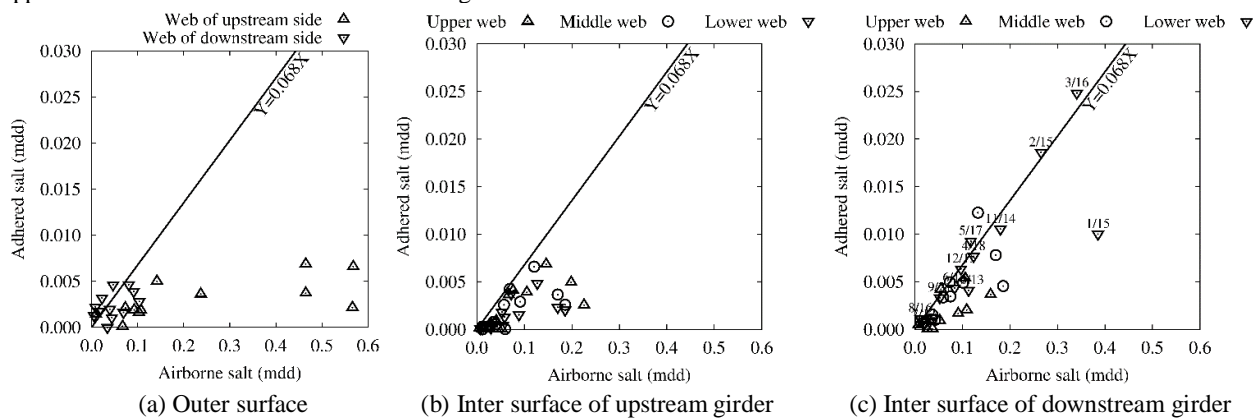


Figure 12. Relation between airborne salt and adhered salt

4.3 Relation between Airborne Salt and Wind Velocity

The relation between mean of prevailing wind and geometric mean of monthly airborne salt is indicated as shown in Figure 11. This figure means airborne salt is given by mean of n -th power of wind velocity. Furthermore, if this relation between airborne salt and wind velocity is established, airborne salt can be estimated by wind velocity without observation of airborne salt in the bridge.

4.4 Relation between Airborne Salt and Adhered Salt

Adhered salt on surface of bridge is redistributed by rainfall, condensation, pile, weather and separation. Here, the relation between airborne salt near the girder and adhered salt in exposure test piece is shown in Figure 12. The Figure 12a indicates results of upper web of outer surface of girder, the figure 12b indicates upper, middle and lower web of inner surface of upstream side girder and the figure 12c indicates downstream side girder. These figures are included the straight line that through the relation between airborne salt and adhered salt at lower web of inner surface of downstream side girder. If the redistribution occurs, adhered salt decreases this line. Adhered salt of outer surface is directly influenced by rainfall. Therefore, adhered salt in the Figure 12a is less than the value on the line. We think that adhered salt in inter surface of surface of girder is less than the value of the line due to condensation, separation and so on.

4.5 Corrosion of Exposure Test Piece

To observe thickness reduction by corrosion, exposure test pieces are set to upper, middle and lower parts of web and both sides of lower flange as shown in Figure 5b. These test pieces are made with weathering steel, and size of the piece is 50mm of length, 50mm of width and 2mm of thickness. The thickness reduction is evaluated by difference of weight of test piece between before and after exposure. Results are indicated as shown in Figure 13. Figure 14 shows the relation between annual average of adhered salt and thickness reduc-

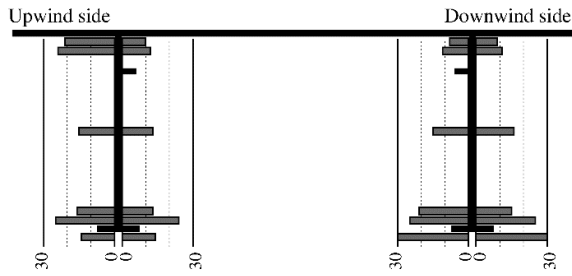


Figure 13. Thickness reduction by corrosion (unit: μm)

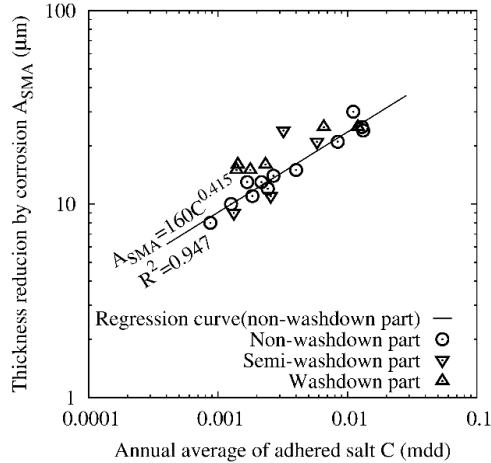


Figure 14. Adhered salt and thickness reduction
*Referred by PWRI, Kozai Club and JBA (2003)

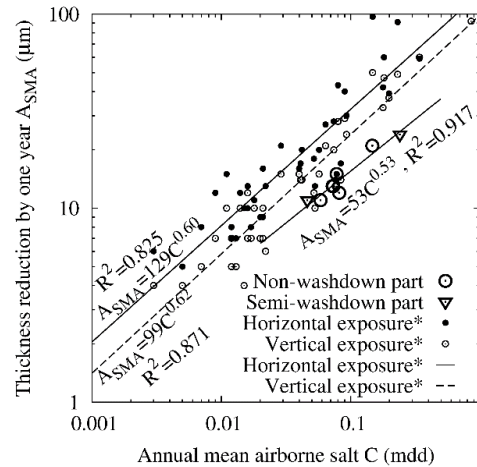


Figure 15. Airborne salt and thickness reduction

tion due to corrosion by one year, and includes regression curve of non-wash down part. Similarly, Figure 15 shows the relation between annual average of airborne salt and thickness reduction due to corrosion by one year. In this figure, Results of the joint research report by Public Works Research Institute of the Ministry of Construction, Kozai Club and Japan Bridge Association (2003) are included. Results of exposure test piece indicate that corrosion can be estimated roughly by adhered salt or airborne salt. In the joint research report, the relation between thickness reduction and airborne salt is obtained by many bridges of various different corrosion environments in Japan, but one position of each bridge is used. On the other hand, results are obtained by many positions of one bridge in this study. There is a large variation in the results of the joint research report as compared with the results in this monitoring bridge, because corrosion environments such as airborne salt, temperature, humidity of each bridge are different.

5 EVALUATION OF ADHERED SALT BY A WIND-TUNNEL TEST

By the above results, thickness reduction of weathering steel by corrosion depends on the airborne salt and the adhered salt at same position. In this section, we discuss what the adhered salt of each position in the bridge can be evaluated by wind-tunnel test. An outline of wind-tunnel test equipment is shown in figure 16, and the cross section and dimension are indicated in figure 17. Model of the bridge is 2.57m away from the blowing position of particle generator, and scale of this model is 1/20. The phenol spherical particles that are close in diameter to airborne salt are used in the experiment. The average of diameter is $8\mu\text{m}$, the range of diameter is from $5\mu\text{m}$ to $20\mu\text{m}$ and the density of phenol particle is $1.25\text{g}/\text{cm}^3$. The velocity of wind in the wind-tunnel test equipment is 2.5m/s. The particles are captured by adhesive tape that is set to the model of bridge. Reynolds number of this wind-tunnel test is different from the actual wind flow in the bridge. However, the separation point of the flow of wind-tunnel test is similar of actual bridge, and density of phenol particle is small enough to follow air stream like airborne salt behavior. Therefore, we think that the result of wind-tunnel test has relatively high accurate. The experiment has been done for 5 times.

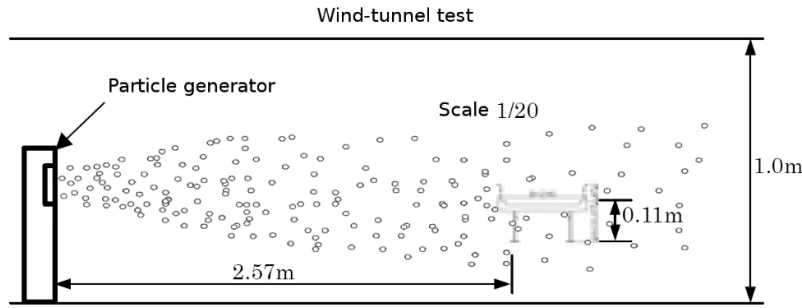


Figure 16. An outline of wind-tunnel test

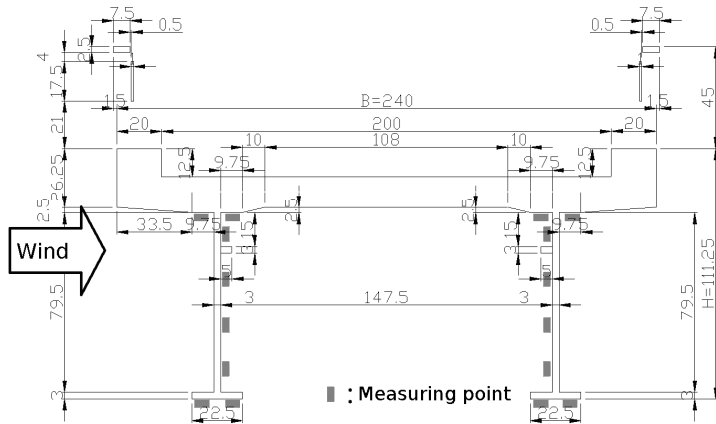


Figure 17. Dimension of bridge model for wind-tunnel test (unit: mm)

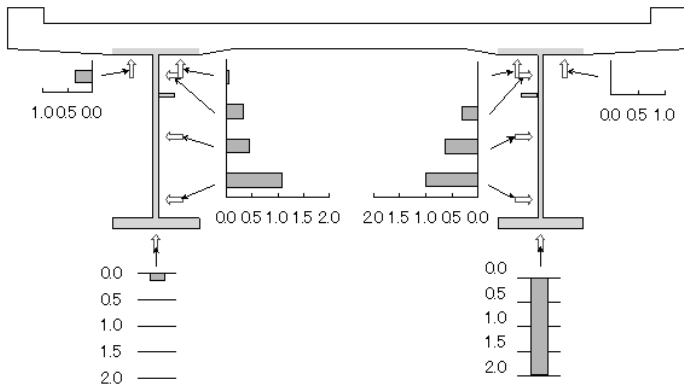


Figure 18. Number of adhered particles of wind-tunnel test
(Normalized value by the adhered particles to the lower web of downwind side girder)

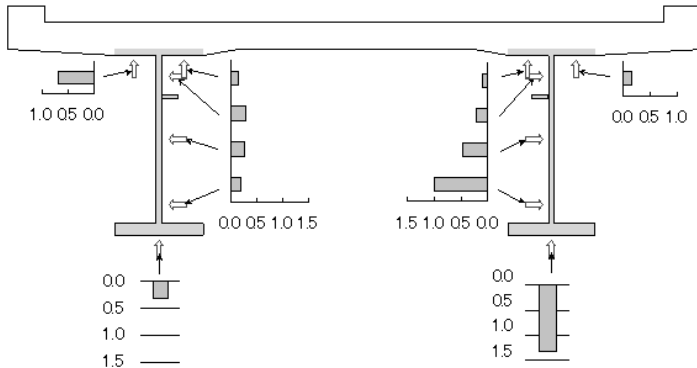


Figure 19. Result of adhered salt of the monitoring bridge
(Normalized value by the annual average of adhered salt to the lower web of downstream side girder)

Result of adhered particles of wind-tunnel test is shown in Figure 18, where value by the adhered particles is normalized by the lower web of downwind side girder. In Figure 19, the normalized adhering salt of exposure test piece of the monitoring bridge is shown. Comparing these figures, the result of wind-tunnel test is

similar the result of airborne salt. Therefore, we consider that the distribution of airborne salt around the bridge section can be estimated by the wind-tunnel test.

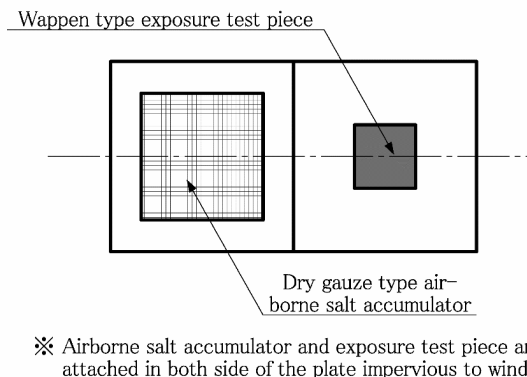


Figure 20. A tool for identification of the relation between airborne salt and thickness reduction by corrosion

6 CORROSION EVALUATION OF THE CROSS SECTION OF BRIDGE

We made clear that airborne salt of each part in the bridge have been same ratio in any month. This means that an airborne salt at anywhere in girder can be estimated by an airborne salt as other position if the ratio of airborne salt as anywhere to other position is clearly. Furthermore, the ratio of airborne salt in section can be obtained by wind-tunnel test. On the other hand, corrosion of weathering steel depends on airborne salt. Thickness reduction A can be expressed by αC^β , where C is the amount of airborne salt, α and β are parameters. Therefore, corrosion behavior of the bridge before construction complete can be made clear by following steps.

Step 1. Identification of the relation between airborne salt and thickness reduction by corrosion: an airborne salt that is measured by covered accumulator under the bridge is obtained as the value of salt of near the girder. Therefore, place the stage near the bridge construction site; we investigate the relationship between airborne salt and thickness reduction by corrosion using a tool such as Figure 20. By this tool in this figure, the relation between airborne salt and thickness reduction at the bridge before construction complete. By this process, following equation is obtained,

$$A = \alpha C^\beta \quad (1)$$

where, A is thickness reduction of steel,
 C is airborne salt
 α and β are parameters

Step 2. Estimation of the airborne salt in section: we obtain the ratio of airborne salt in section by using the wind-tunnel test, and measure airborne salt near the bridge where of is scheduled. By these results, actual airborne salts near bridge section are obtained by the ratio of airborne salt obtained by wind-tunnel test and measured airborne salt product.

Step3. Evaluation of thickness reduction in section: thickness reduction of the bridge before completion will be evaluated by the results above steps.

7 CONCLUSIONS

In this paper, the application standard of weathering steel to bridges in Japan is explained, and the influence of environmental factors on the rust distribution of the bridge section is discussed by using observed data for one year in a two-girder bridge. Furthermore, a new approach method to evaluate partial corrosion level is proposed by using wind tunnel test. New knowledge obtained by this paper is summarized as follows:

- i. The ratio of airborne salt can be obtained by using wind tunnel test including particles.
- ii. Rust distribution of girder is affected by wind flow included airborne salt.
- iii. The amount of airborne salt is expressed by the power of function of wind velocity.
- iv. Thickness reduction per one year by corrosion is correlated with airborne salt.

v. Airborne salt of each part in the bridge have been same ratio in any month.

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