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Corrosion Risk Management Methods to Realize Long-term Durability of Weathering Steel Bridges

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Abstract

In expectation to reduce maintenance costs incurred through repainting, the application of weathering steels to bridges is increasing. Applicability limit is enlarged by recently developed nickel containing advanced weathering steels. In order to realize long term durability of weathering steel bridges, one has to assess at the planning and/or designing stages, that atmospheric corrosiveness of the construction site is within the applicability limit of the weathering steel to be applied. Also, adequate maintenance is required to cope with unpredictable part in corrosion risks. In this report, corrosion risk management technologies developed by the authors are systematically proposed in terms of methods for selection of adequate weathering steels, methods for monitoring and diagnosing rust state of existing bridges, together with efficient and effective methods for repair as a contingency plan.

1. Introduction

Weathering steel that can be used uncoated is an attractive material since one can reduce life cycle cost (LCC) of the steel structures, which are kept in service for a particularly long periods. In Japan, nearly 75% of the demand for weathering steel is for bridges. Those which rely largely on the use of weathering steel for corrosion prevention are called weathering steel bridges. As shown in **Fig. 1**, the proportion of weathering steel applications to all steel bridges has been increasing steadily.

The concept and rules of application of weathering steel to bridges have been prepared one after another as actual use of weathering steel is increased[1]. In the 2002 revision of the Specifications for Highway Bridges[2], the application of weathering steel is treated as one of the methods to prevent corrosion of steel bridges. On the other hand, among existing bridges, some were installed in areas where weathering steel can hardly be applied in light of the current provisions, and some are adversely affected by the use of de-icing salt on the road. Besides, universal guidelines how to select adequate weathering steel and surface treatment, if necessary, were not completely established. Therefore, engineers and scientists in government, academia and industry cooperate to review and revise the current

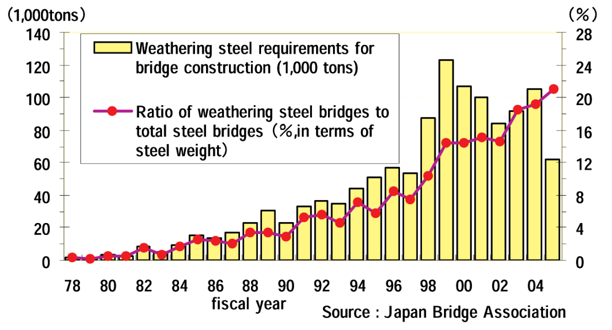

Fig. 1 Increasing applications of weathering steel bridges

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provisions in terms of application of weathering steels, to improve techniques for inspection and diagnosis, and to refresh the classical repair painting methods of corroded steel bridges, in accordance with the performance-based design system[3-5].

In this paper, we shall describe the recently developed techniques for corrosion risk management, including materials selection methods, bridge inspection methods and repair painting methods for steel bridges, which help minimize the maintenance cost of steel bridges.

2. Concept of Corrosion Prevention Design Using Weathering Steel

Characteristically, in appropriate environmental conditions, weathering steel forms a dense layer of protective rust on the surface, which restrains corrosion of the steel. The condition of the protective rust depends on the severity of the corrosive environment in which the steel is placed. It should be noted that corrosion rate increases in the atmospheres containing a relatively large amount of salt, and in the environments in which the steel surface is frequently wet. The relationship between the condition of protective rust and the loss of steel weight due to corrosion is shown in **Fig. 2**[5, 6].

This is not to imply that weathering steel is completely free from corrosion. However, the protective rust formed on its surface restrains the development of thick rust to such a degree that no special maintenance is required of the steel members. Thus, the prescribed durability of a weathering steel bridge can be secured by controlling the loss of steel thickness during the design service period of the bridge within predictable limits. Weathering steel is not totally free of maintenance. In order to bring the superior corrosion resistance of weathering steel bridges into full play, it is necessary to provide suitable measures at all stages of structural planning, designing, constructing, and maintaining the bridge to which they are is applied.

Table 1 shows the three levels of corrosion resistance required of weathering steel bridges. For ordinary weathering steel bridges, Level I is sought[5]. Here, a target of average thickness loss of 0.5 mm per 100 years on each side was set. By taking such corrosion resistance in to considerations at bridge design stage, its load bearing capacity will remain sufficient for prolonged period of time.

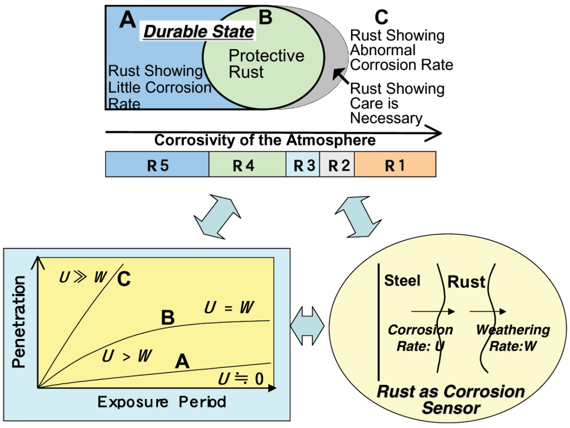

Fig. 2 Relationship among durable state concept, rust appearances, and penetration curves of weathering steels

Table 1 Levels of anti-corrosion design for weathering steel bridges

I	The level in which corrosion loss to occur during design service period little affect designed load capacity of a bridge. Target: thining per side is less than equal 0.5mm/100years. Rust appearance rate is to be kept from 3 to 5.
II	The level in which corrosion loss to occur during design service period little affect designed load capacity of a bridge, with setting of corrosion margin. Target: thining per side is less than equal 1mm/100years. Rust appearance rate is to be kept more than 2.
III	The level applicable to exchangable parts of a bridge. Rust appearance rate is to be kept more than 1.

3. Corrosion Risk Management of Weathering Steel Bridge

Under general conditions, the design service period of bridges to be constructed in Japan is 100 years as a rule of thumb. On the other hand, there are cases in which bridges are exposed to unexpectedly severe environmental conditions affected by partial leakage of water from upper structural defects. In such cases, unusual corrosion of the weathering steel may occur. In order to reduce life cycle cost of a weathering steel bridge, it is of prime importance to ensure the long-term durability of the bridge by minimizing the required maintenance. In this respect, it is considered most effective to predict the risk of corrosion, and then monitor and reduce such risk. The risk controlling points (RCP) are shown in **Fig. 3**. At the planning and design stages, it is especially important to select the optimum steel material according to the corrosive properties of the atmosphere at the bridge construction site, and to design an anti-corrosion structure which facilitates maintenance of the bridge. While the bridge is in service, monitoring the condition of the rust and early detection of abnormal conditions are necessary. In the event that an abnormal condition is detected, it is important to investigate the cause, and apply adequate repairs if necessary[7].

4. Method of Utilizing Weathering Steel in Appropriate Environments on a Performance Basis

4.1 Advanced weathering steels and evaluation of their performances

Uncoated weathering steel SMA-W specified in JIS G 3114 (SMA) is generally used as the structural material for bridges in Japan. However, since the application of SMA-W is limited to areas where the concentration of airborne salt is low enough (0.05 milligrams per square decimeter per day (mdd) or less). Therefore, devel-

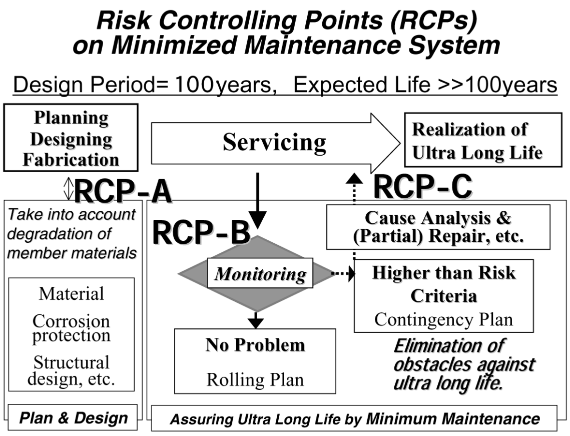

Fig. 3 Minimum maintenance bridge concept and controlling points for corrosion risks

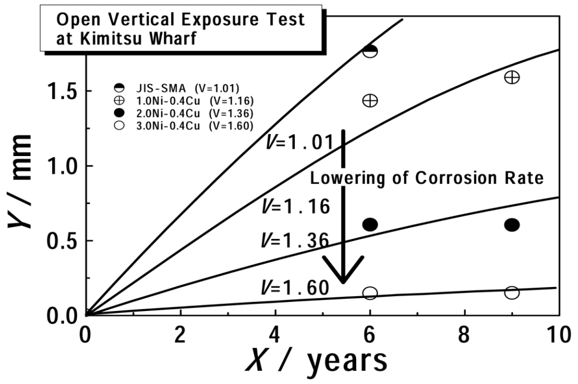

Fig. 4 Exposure test results for various weathering steels

opment of advanced weathering steels with superior resistance against air born salt has been called for.

Based on the fact that increasing the amount of nickel added to steel increases the steel's corrosion resistance against salt damage, Nippon Steel commercialized 3%-Ni advanced weathering steel[8] in 1998, together with suitable welding material and high-strength bolt. The cumulative total of this advanced weathering steel applied to steel bridges reached 24,500 tons by the end of fiscal 2006.

The weathering performances of steel materials which differ in chemical composition are evaluated by means of suitable accelerated weathering tests or exposure tests simulating the environmental conditions of the construction site. **Fig. 4** shows examples of the exposure test results. In the figure, the weathering alloy index V is the one used to determine the effect of each individual alloying element on the weathering properties of the steel[9]. For instance, the value of V for SMA-W is approximately 1.00, 3%-Ni advanced weathering steel has a V-value of 1.50. At present, Nippon Steel is manufacturing intermediate weathering steel whose V-value is 1.20.

4.2 Method of evaluating environment in which weathering steel is applied

Basically, the applicability of a weathering steel bridge is determined based on the loss of weathering steel thickness due to corrosion estimated from the results of an evaluation of the environmental conditions at the construction site. The concentration of deposited salt and the degree of moisture that influence the corrosion rate of the individual parts of the bridge differ according to the local characteristics of the bridge construction site. Thus, relationships among topography, bridge structures and local environments unique to the individual parts or members of the bridge must be considered.

The local environmental conditions that influence the bridge as a whole are evaluated during the structural planning. The classical method to the SMA weathering steel, in which the amount of airborne salt is used as a criterion for judgment on the applicability of a weathering steel bridge, is based on the results of exposure tests and measurements of airborne salt at the lower place in between inner girders of 41 bridges throughout the country[10]. It seems that when the amounts of airborne salt measured with conditions that the sides are left open, the measured values become much larger than those with both sides sheltered by girders. **Fig. 5** shows examples of distributions of wind velocity and airborne salt concentrations around a bridge girder simulated using an I-section for the exposure test. It has been confirmed that with the gauze method also, the amount of airborne salt measured inside the girder is smaller than that measured outside the girder[11]. With an I-section, airborne salt and dew

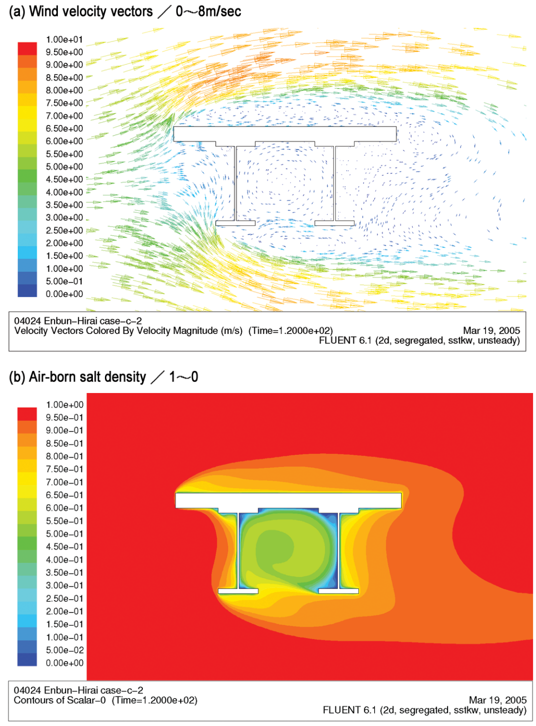

Fig. 5 Simulated distribution of wind and air-born salt around a plate girder bridge

tend to reside on the upper surface of the lower flange inside the girder. From the standpoint of preventing corrosion, a round or vessel-shaped section is advantageous because it minimizes the accumulation of residual salt and dew[12].

When the amount of airborne salt is used as an index to evaluate the environment, it is necessary to note the differences arising from the place and direction of measurement, and fluctuations due to measurement timing. The simple and accurate methods of evaluating the local environment that Nippon Steel is developing and putting into practical use are described in the following section. The local environmental conditions of the girder ends, etc. are difficult to predict during the planning and design stage. Therefore, it is desirable that a suitably detailed structure be selected, including the application of partial coating.

4.3 Method of predicting loss of thickness of weathering steel due to corrosion

Nippon Steel has proposed a mathematical model to predict corrosion rate of weathering steels as in a software called YOSOKU®, based on the durable state concept in which steel is stabilization by protective rust formation or by lower corrosiveness of the atmosphere[13]. In addition, the company has built a regional meteorological database and simple methods of estimating the amounts of airborne salt and sulfur oxides. **Fig. 6** shows the simulation software YOSOKU®.

It is already known that the loss of thickness, Y (mm), of weathering steel SMA due to corrosion can be expressed by the following equation.

$$Y = A_{SMA} \cdot X^{B_{SMA}} \quad (1)$$

where X denotes the number of years elapsed from the start of exposure, and A_{SMA} and B_{SMA} denote the rate parameters determined by the environment to which the steel is exposed and the alloy composition, respectively.

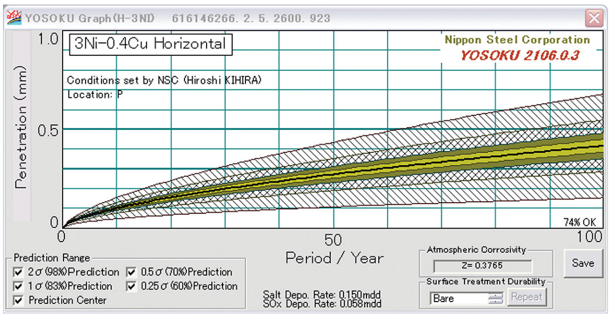

Fig. 6 Corrosion prediction software, called YOSOKU®

The value of A_{SMA} corresponds to the value of Y (loss of steel thickness due to corrosion) when $X = 1$ (year). Since it quantitatively indicates the corrosiveness of the local environment to which SMA is exposed, it is called the local corrosiveness index. On the other hand, the value of B_{SMA} corresponds to the reciprocal of the degree of decrease in corrosion rate due to an increase in the protective action of the rust. Therefore, the value of $1/B_{SMA}$ is called the index of the effect of formation of protective rust. By formulating the relationship between A_{SMA} and B_{SMA} on using exposure test results as mentioned earlier, it became possible to calculate the loss of steel thickness due to corrosion from A_{SMA} using the procedure as shown in **Fig. 7**[5, 13].

The lower part of the inside of the girder that was subjected to an exposure test was not subjected to any rain and was in a relatively severe corrosive environment. Therefore, it is treated as the representative part.

In the case of nickel-alloyed weathering steel, the corrosion rate parameters are assumed to be A_S and B_S. Each of the ratios of A_S to A_{SMA} and of B_S to B_{SMA} is related to the appropriate weathering alloy index (V-value) to enable conversion of the rate parameters through the following procedure: A_{SMA} value → B_{SMA} value → A_S value and B_S value.

The basic functions of rust controlling surface treatment for weathering steel is to support the formation of protective rust, and to restrain the outflow of the initial fluid rust. Basically, weathering steel should be used in such an environment that the steel does not require such a surface treatment. In the case that an effect of the rust controlling surface treatment on restraining corrosion rate of weathering steel, it is possible to apply it even beyond the applicability limit of its bare use, provided that the predicted loss of steel thickness due to corrosion suggests that Level I corrosion resistance will be attainable.

4.4 Method of evaluating applicability of weathering steel at specific sites using short-term exposure test

The above exposure test which simulates the actual environmental conditions enables direct and accurate evaluation of the amount of corrosion; however, it requires relevant data collected over several years. A short-term exposure test which applies the method of predicting the loss of steel thickness due to corrosion has been developed[5]. In this exposure test, the loss of steel thickness due to corrosion in the first year of the test is first evaluated as the environmental corrosiveness index A_{SMA} at the construction site and then, the index is compared with the threshold value for the appropriate corrosion resistance level to evaluate the applicability of the steel. This exposure test is carried out on a covered platform at the planned construction site or on an existing bridge in its vicinity. The measured value is used as the corrosive environment index for the representative part of the bridge. The threshold value for the Level I for SMA steel is assumed to be 0.030mm[5].

4.5 Method of selecting weathering steel

Once the local environmental corrosiveness index A_{SMA} is determined, it is possible to calculate the predicted loss of steel thickness due to corrosion. Thickness loss Y during 100 years ($X = 100$) for a weathering steel may be altered by kind of weathering steel with alloy index V. By using the A_{SMA}-V-Y relationship shown in **Fig. 8**, it is possible to select an adequate weathering steel which meets the anti-corrosion requirements, which are determined by discussion how much the loss of steel thickness due to corrosion should be considered at the design stage[5, 14].

In corrosion prediction, the average amount of corrosion is calculated with statistical probability taking into account the errors due to the dispersion environmental factors. In Fig. 8, however, calculated values of steel thickness loss due to corrosion with a normal probability of 50% are shown.

5. Methods of Proper Maintenance to Provide Against Unexpected Environmental Deterioration

5.1 Corrosion risk matrix

In the maintenance of a weathering steel bridge, it is considered effective to implement corrosion risk management assessing that the bridge is normal when the steel corrosion rate is well within the allowable limit as set in the planning/design stage, that the bridge requires careful observation when the steel corrosion rate is close to the allowable limit, and that the bridge is abnormal if the steel corrosion rate is higher than the allowable limit.

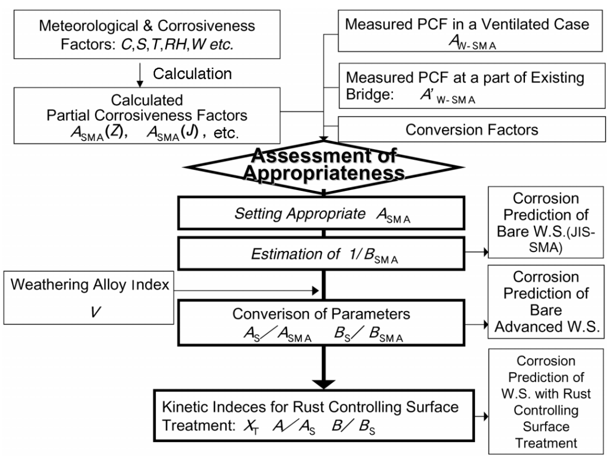

Fig. 7 Assessment and computational flow of corrosion prediction

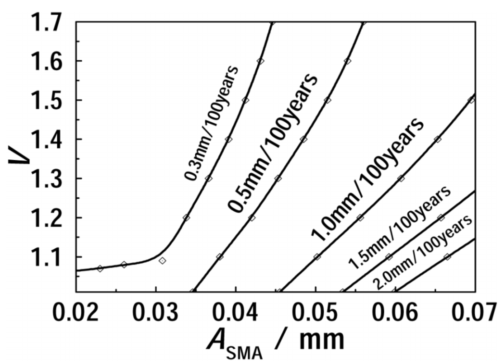

Fig. 8 Corrosion prediction chart for various weathering steels

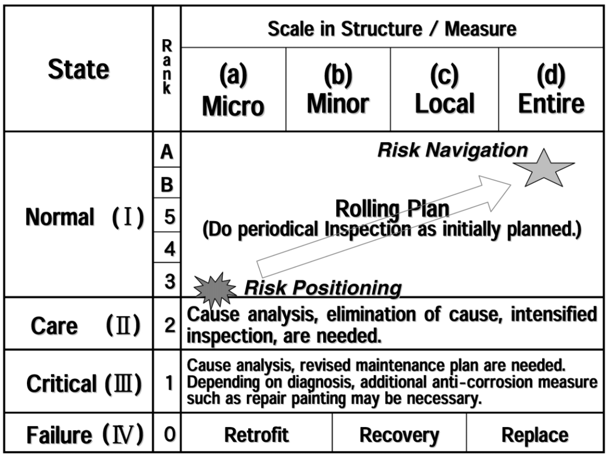

Fig. 9 Corrosion risk matrix for steel bridges

The likelihood of failure caused by corrosion and the scale of the damage if it occurs are combined as risk index. A corrosion risk matrix as proposed in **Fig. 9** is convenient for discussing reasonable priorities for measures to avoid serious damage caused by corrosion[7)].

From the LCC standpoint, the occurrence of an abnormal condition does not necessarily mean a failure. As long as the abnormal condition is detected in early stage, one can take appropriate actions to avoid catastrophic failure. For example, suitable measures to eliminate the cause or to take additional anti-corrosion measures will navigate the corrosion risk to safe side by which the LCC can be minimized.

5.2 Method of monitoring rust conditions

The corroding condition of the weathering steel can be monitored by the rust appearance rating method. However, since this method is based on visual inspection, it is not very easy for inexperienced inspectors. In order to reduce the risk of human error, a quantitative diagnostic method applying the ion transfer resistance method (see **Fig. 10**) has been put in to practical use[15)].

When the rust appearance rating is “2” (scaly rust) or “1” (thickly layered rust), estimating the loss of steel thickness due to corrosion is subject to wide variations. An exposure test method in which thin test pieces made of weathering steel are attached to the bridge as shown in **Fig. 11** has been proposed. By using this method, it is possible to quantify the corrosion rate at each individual part of the bridge and thereby to improve the accuracy of corrosion prediction[16)].

5.3 Efficient method of primary treatment for repair coating

In many cases, steel bridges experience local corrosion caused by water leaking and residing at the end of girders. When unusual rust due to salt deposition occurs, one can hardly remove it even by blasting. Thus it is also difficult to carry out primary treatment using a conventional power tools. Under these conditions, repair coatings cannot have sufficient durability.

In order to resolve the above problem, Nippon Steel created a motor-driven tool made of stainless steel with grains of man-made diamond for the primary treatment of damaged steel parts. In a test, salt water was sprinkled over a weathering steel plate to cause unusual rust to develop to a thickness of 1.5 mm and an attempt was made to remove the rust using the tool. As shown in **Fig. 12**, the rust could be removed easily[17)]. This tool will significantly reduce the measures needed to control dust and noise in the blasting process, making it possible to improve the efficiency and durability of partial repair coating.

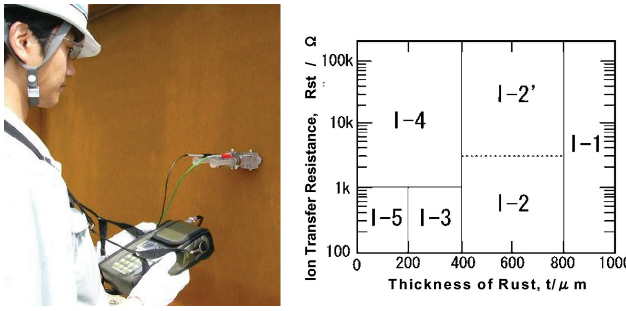

Fig. 10 Diagnosis of rusting state of an existing weathering steel bridge obtainable by a developed instrument, R.S.T.

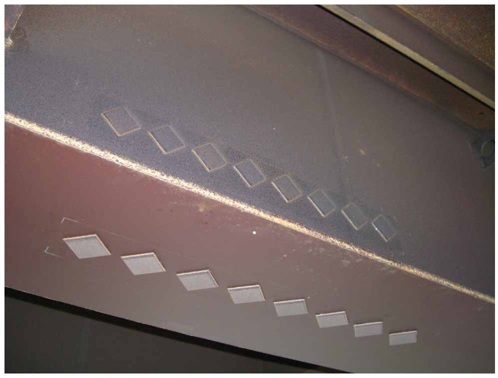

Fig. 11 Exposure test at an existing steel bridge using attachable small test pieces made of weathering steel

Fig. 12 Removing of thick adherent rust on weathering steel by a developed instrument

Considering the characteristics of diamond, it is desirable from the standpoint of work efficiency and tool life that the degree of primary treatment should be such that 60% or more of the metal surface is exposed. Nippon Steel together with Nittetsu Anti-Corrosion Co., NS Materials Co., and Dai-Nippon Toryo Co. have also developed an organic zinc-rich primer applicable to that level of primary treatment[17)]. At present, the durability of this primer is being tested.

6. Conclusion

With the aim of minimizing the maintenance cost of bridges, Nippon Steel has developed advanced weathering steels and has proposed a corrosion risk management methods. In addition, the company has been taking initiative in development of methods to evaluate corrosion conditions of weathering steels: for example, inspection and diagnosis methods, repairing methods, and corrosion prediction methods to support the anti-corrosion design of weathering steel bridges. Also to predict the corrosion loss of existing weathering steel bridges, exposure test methods using attachable test pieces have been proposed by Nippon Steel, which may be used in the planning and maintenance of actual bridges. These proposals are already taken up as themes for R&D projects lead by public organizations as core technologies to enhance the method of evaluating the environment in which weathering steel is applied. A new method of primary treatment for repair coating has also been co-developed by Nippon Steel, Nittetsu Anti-Corrosion Co., Dai Nippon Toryo Co. and Nippon Steel Materials Co. While the durability of the treatment is still being tested on actual bridges, the method was proved to be practical for partial repair of weathering steel bridges.

We hope that these methods as described in this paper will help to enhance the reliability of weathering steel bridges.

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