NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 110 SEPTEMBER 2015

Technical Report

UDC 669 . 14 . 018 . 821 : 669 . 15 ' 24 - 194 . 2

Long-term Follow-up Survey on 3%Ni-added High-performance Weathering Steel (NAW-TEN™15) in High Airborne Salt Concentration Environment and Risk Management of Weathering Steel Bridges

Makoto NAGASAWA* Ryuichi ANDO
Yoshiyuki HARADA Mutsuto TANAKA
Motohiro OKUSHIMA Masahide TAKAGI

Abstract

To achieve minimum maintenance work of steel bridges, we developed the world's first 3%Ni-added high-performance weathering steel (NAW-TEN™15). It was applied to railway bridges near the Sea of Japan in 1998 and the outward appearance of the bridges at 15 years later showed good condition. We have also conducted outdoor exposure tests near the bridges. As a result, the corrosion loss of the developed weathering steel was approximately two thirds that of JIS-SMA which is a weathering steel standardized by the Japanese Industrial Standard. Also the corrosion loss of the 3%Ni-added high-performance weathering steel was estimated at 0.17mm 100 years later. Recently, demand of further durability for existing steel bridges by adequate maintenance has been increasing. In accordance with the demands, inspection methods, corrosion diagnosis systems and repair methods that are easy to use for the worker in charge have been developed. This paper reveals that, the results of long term durability investigation of 3%Ni-added high-performance weathering steel, inspection methods, corrosion diagnosis systems and repair methods are essential for achievement of minimum maintenance work.

1. Introduction

Weathering steel is a low-alloy, corrosion-resistant steel containing very small amounts of alloying elements (Cu, Ni, Cr, P, etc.), which form a dense, protective rust layer on the steel surface, and thereby shows excellent corrosion resistance to the steel used in the atmospheric environment.[1] In 1968, low-P-based weathering steels were designated by JIS as "hot-rolled atmospheric corrosion-resistant steels for welded structure" (JIS-SMA in JIS G 3114). Then, as steel materials that help reduce the cost of maintenance of steel structures, weathering steels began to be applied mainly to bridges. Through the establishment of the concept and rules for application of weathering steels to bridges by a joint study of Public Works Research Institute of the Ministry of Construction, Kozai Club, and Japan Bridge Association,[2] etc., weathering steels came to be included in such design standards as the Road Bridge Specification with Explanations[3] and the Railway Structures Design Standard with Explanations.[4] In recent years, weathering steel bridges account for about 25% of newly constructed steel bridges (**Fig. 1**).

According to the above joint study, it was found that weathering steels did not form a protective rust layer on the steel surface in coastal environments containing a comparatively large amount of airborne salt and that JIS-SMA was applicable only when the airborne salt area was not more than 0.05 mg/100 cm^2/day (NaCl: 0.05 mdd) (**Fig. 2**).[3] From the perspective of reducing the life cycle cost

* Researcher, Plate & Shape Research Lab., Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

of a steel bridge, using uncoated weathering steel is advantageous because it need not repaint the bridge. Therefore, there was growing demand for uncoated weathering steel even in coastal regions.

In 1997, Nippon Steel & Sumitomo Metal Corporation developed and put on the market a 3%Ni-added high-performance weathering steel together with an exclusive welding material and high-strength bolts (see **Table 1** for their chemical compositions) that can be applied even in a high airborne salt environment (airborne salt area > 0.05 mdd) wherein JIS-SMA cannot be used.[5, 6] The newly developed high-performance weathering steel gives the rust layer an ion-exchange capability that concentrates chlorine ions to the outer rust layer and sodium ions to the inner rust layer so as to restrain the penetration and concentration of chlorine ions into the steel surface, and inhibits the decrease in pH at the inner rust layer and the interface with the steel substrate and thereby lowers the corrosion rate of steel markedly.[6] The 3%Ni-added high-performance weathering steel with supplemental rust controlling surface treatment was applied for the first time in 1998 to the girders and piers of the viaduct of the Hokuriku Shinkansen over the Hokuriku Highway located about 600 m away from the coastline of Oyashirazu in the western part of Niigata Prefecture (**Fig. 3**).[7–9] Since then, the nickel-based high-performance weathering steels of Nippon Steel & Sumitomo Metal have been applied to a total of 93 railway and road bridges (total steel consumption: about 31 000 tons) as of the end of March 2013 (**Fig. 4**).

In addition, with the aim of achieving "minimum maintenance" of steel bridges, Nippon Steel & Sumitomo Metal has been pressing ahead with not only the development of new steel products but also the development and systematization [10, 11] of application techniques, such as the long-term corrosion loss prediction technology (YOSOKU™) [12, 13] as a tool for judging the applicability of a weathering steel and the quantitative rust state diagnostic technology (RST: Rust State Tester) [14, 15] for maintenance management of weathering steel bridges. Thus, the company has been developing both hardware and software.

In this paper, we shall describe the appearance change of the viaduct of Hokuriku Shinkansen over the Hokuriku Highway to which our 3%Ni-added high-performance weathering steel was ap-

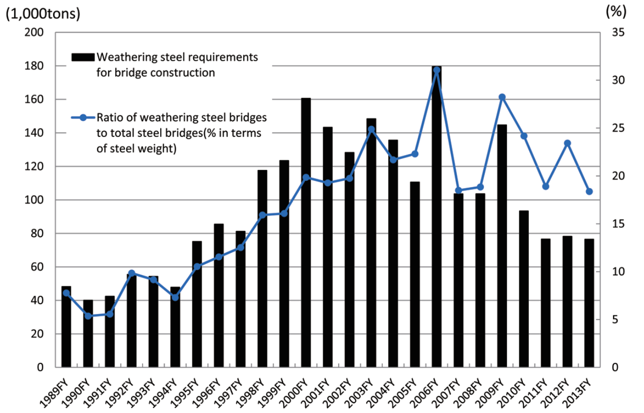

Fig. 1 Application transition of weathering steel bridges (courtesy: Japan Bridge Association)

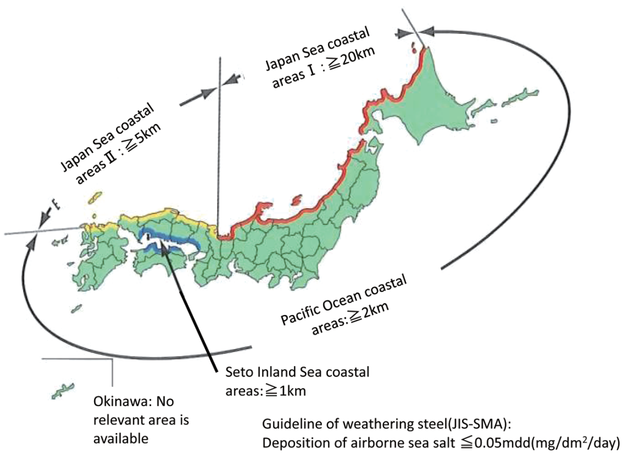

Fig. 2 Application guideline of weathering steel for road bridges (bare)

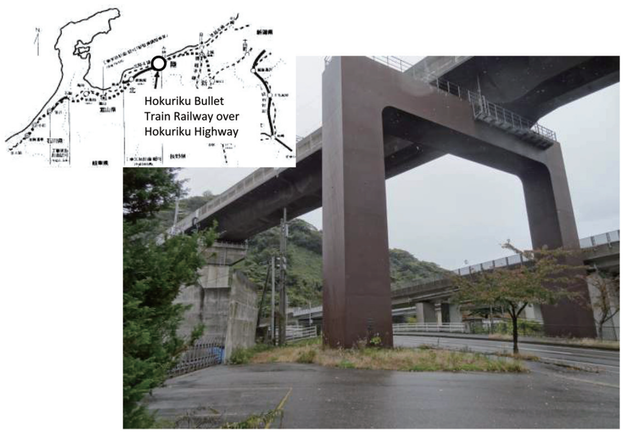

Fig. 3 Appearance of 3%Ni-added high-performance weathering steel bridge after 15 years

Table 1 Chemical compositions of base metal, welding material, high strength bolt of 3%Ni (mass%)

	Grade		C	Si	Mn	P	S	Cu	Ni	Cr	V value
Base metal	3%Ni	Test specimen	0.10	0.20	0.60	0.005	0.001	0.38	3.04	0.02	1.56
		Specification	≦ 0.18	0.15/0.65	≦ 1.40	≦ 0.035	≦ 0.035	0.30/0.50	2.50/3.50	≦ 0.08	≧ 1.50
	JIS G 3114	Test specimen	0.13	0.45	1.01	0.015	0.005	0.33	0.09	0.47	1.01
		Specification	≦ 0.18	0.15/0.65	≦ 1.40	≦ 0.035	≦ 0.035	0.30/0.50	0.05/0.30	0.45/0.75	---
Welding material	NSSW SF-50WN	Example	0.04	0.25	0.49	0.008	0.005	0.30	2.70	-	1.53
High strength bolt	S10TMR	Example	0.22	0.21	0.50	0.009	0.004	0.35	3.00	-	1.74

$$V = 1 / \{(1.0 - 0.16\,[C]) \times (1.05 - 0.05\,[Si]) \times (1.04 - 0.016\,[Mn]) \times (1.0 - 0.5\,[P]) \times (1.0 + 1.9\,[S]) \times (1.0 - 0.10\,[Cu]) \times (1.0 - 0.12\,[Ni]) \times (1.0 - 0.3\,[Mo] \times (1.0 - 1.7\,[Ti])\}$$

Range of V value $0.9 \leqq V \leqq 2.5$

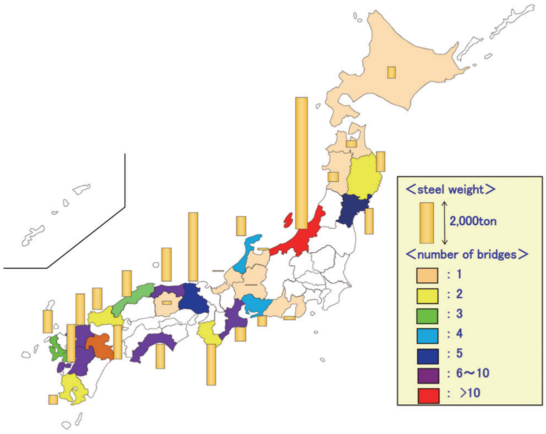

Fig. 4 Practical applications of Ni-added high-performance weathering steel bridge

plied for the first time (1998) and the results of evaluation of the steel corrosion resistance by an exposure test conducted in the neighborhood of the bridge.[7–9] In addition, we shall review the present condition of inspection and diagnosis of weathering steel bridges and the repair techniques applicable to them.

In view of the subsequent commercialization of several types of nickel-added high-performance weathering steels by a number of steelmakers, a weathering alloy index (V-value) considering airborne salt damage resistance has been proposed as a result of research conducted to objectively evaluate the corrosion resistance of weathering steel.[16, 17] An example of the calculation of the V-value of our nickel-added high-performance weathering steel is shown in Table 1.

2. Evaluation of Secular Changes of 3%Ni-Added High-Performance Weathering Steel in 15 Years[9]

Figure 3 shows the appearance of the 3%Ni-added high-performance steel (subjected to supplemental rust controlling surface treatment) that was applied to the viaduct of Hokuriku Shinkansen over the Hokuriku Highway (hereinafter referred to as "the bridge") 15 years after construction of the bridge. The bridge has a closed-type girder structure (4-span continuous composite box girders "vessel shaped girders" and 3-span continuous concrete-filled steel pipe combined girders "steel girders") to secure adequate ventilation and drainage. Thus, the bridge is constructed in such a way that most part of it is effectively cleaned by rainwater. In fact, the bridge is still in good condition even after 15 years. In the neighborhood of the bridge, an exposure test using test pieces and a simulated bridge prepared from newly-fabricated steel plate was started before the bridge was built at the site. The exposure test has been continued to examine the secular changes of the weathering steel. The amount of adhered salt to the inner and outer the girders of the simulated bridge was measured for one year. It was 0.244 mdd on average for the outer girders (under condition without eaves) and 0.036 mdd on average for the inner girders (under condition protected by eaves at the side) (**Figs. 5** and **6**).[8]

The exposure test was conducted using test pieces without shelter in horizontal position considering the bridge construction that allowed for cleaning in rainwater. **Figure 7** shows the secular change in corrosion loss of the steel plate per side calculated weight loss. The corrosion loss of uncoated 3%Ni-added high-performance weathering steel was about 2/3 that of JIS-SMA. The test piece that

(a) Inside of the bridge (b) Outside of the bridge

Fig. 5 Airborne salts measurement situation at the inner and outer girder of the simulated bridge

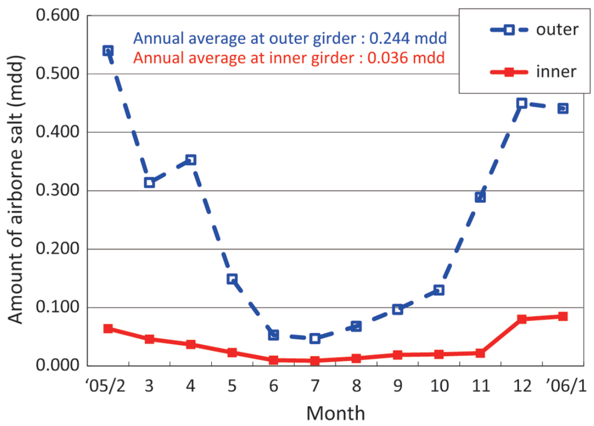

Fig. 6 Airborne salts measurement result (2005) at inner and outer girder

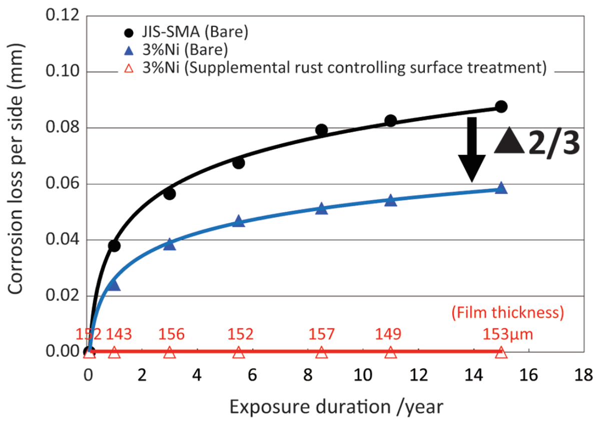

Fig. 7 Secular change of corrosion loss

had been subjected to the same supplemental rust controlling surface treatment as the bridge showed very little change in appearance even after 15 years of exposure. The corrosion loss of the test piece was also minimal. **Figure 8** shows the secular change in ion transfer resistance of uncoated exposure test pieces. Each of the numbers in Fig. 8 indicates the number of years of exposure. With the lapse of time, both JIS-SMA and 3%Ni-added high-performance weathering steel show a shift from the non-growth rust region (I-5) to the protective rust region (I-4), indicating that the protective rust layer was formed on the steel surface.[18]

The corrosion loss of weathering steel, Y (mm), with the lapse of

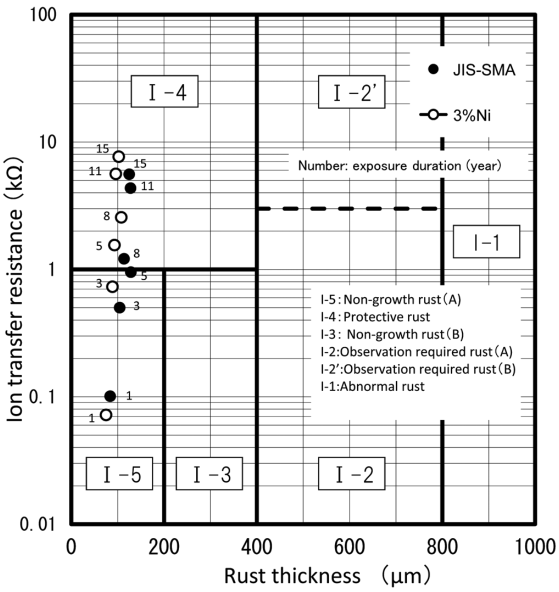

Fig. 8 Secular change of rust thickness and ion transfer resistance

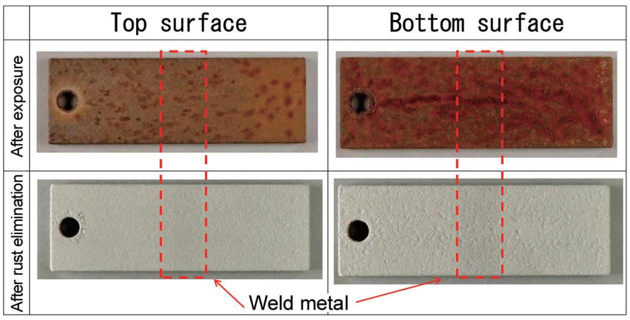

Fig. 9 Appearances of weld joints of 3% Nickel-added high-performance weathering steel after exposure test (15 years)

time is expressed by the power law $Y=AX^B$ (X: elapsed time in years). Therefore, we estimated the corrosion loss of 3%Ni-added high-performance weathering steel over a long time period using the results obtained in 15 years. As a result, it could be expressed as $Y=0.025X^{0.34}$ (value of A: 0.025, value of B: 0.34). Hence, the corrosion loss in 100 years becomes 0.17 mm. Thus, 3%Ni-added high-performance weathering steel would assume the good condition—the cumulative corrosion loss in 100 years shall not exceed 0.50 mm—specified in the Design Standards for Railway Structures, etc. with Explanations.[4)]

Figure 9 shows the appearances of test pieces of the welded joint of 3%Ni-added high-performance weathering steel after the exposure test. **Figure 10** compares the corrosion loss between the base metal and the welding material. It could be confirmed that even after 15 years, both the base metal and the weld zone of the test pieces remained normal in appearance after the removal of rust and that there was very little difference in corrosion loss between the base and weld metals.

Unlike the bridge employing vessel-shaped and steel-pipe girders, the simulated bridge was of two-main-girder construction with inner parts from where deposits of airborne salt, etc. could hardly be washed away by rainwater. Namely, it was considered that the amount of adhered salt to the inner girder of the simulated bridge

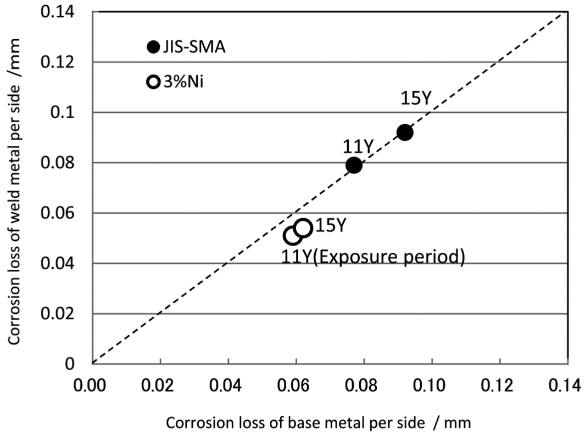

Fig. 10 Comparison of corrosion loss between base and weld metal

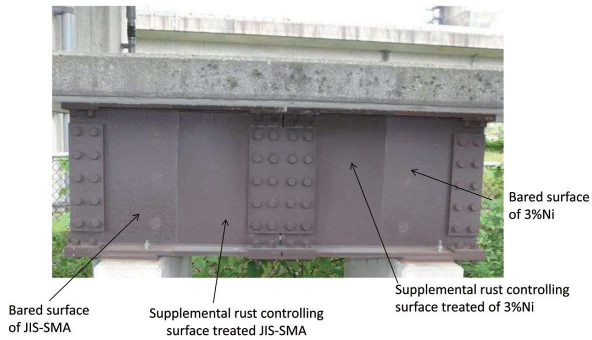

Fig. 11 Appearance of simulated bridge (exposure after 15 years)

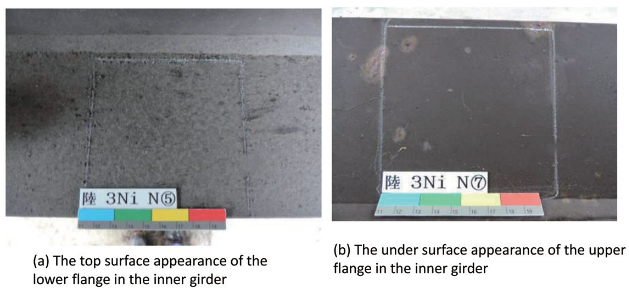

Fig. 12 Appearance of supplemental rust controlling surface treatment (exposure after 15 years)

was larger than in the case of the bridge. In other words, the simulated bridge was exposed to a high airborne salt environment. **Figure 11** shows the appearance of the simulated bridge after 15 years of exposure test, and **Fig. 12** shows the top and bottom steel surfaces subjected to supplemental rust controlling the surface treatment inside the girder. The appearance rating was "4" (good protective rust) for the bare steel and "A" (with supplemental rust controlling surface treatment film and without discoloration/fading) for the steel subjected to supplemental rust controlling surface treatment. Thus, the steel surfaces were found to be in good condition.

Figure 13 shows the rating of appearance and the amount of adhered salt[8)] at various parts of 3%Ni-added high-performance weathering steel subjected to supplemental rust controlling surface treatment inner girder of the simulated bridge. For the upper surface

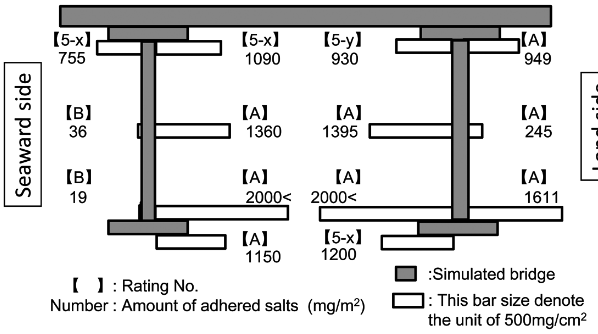

Fig. 13 Amount of adhered salts on simulated bridge

of the under flange of the inner girder where the amount of adhered salt is the largest, the appearance rating [19] was "5-x," which is the combination of "5" (no progress of corrosion; thin layer of rust) and "x" (rust on rust-controlling surface < 3%). For several other flange parts, the appearance rating was "5-x" or "5-y" (rust ratio < 30%). However, most of the parts, including the upper flange inside the girder, were rated "A" (same as parts outside the girder) or "B" (with discoloration/fading). Thus, as a whole, the corrosion protection performance was good, with no rust appearing on the steel surface.

3. Comparison of Corrosion Loss Predicted by Long-Term Corrosion Loss Prediction Technology (YOSOKU) with Corrosion Loss Based on Exposure Test

The corrosion protection performance of steel varies markedly according to the corrosiveness of the environment surrounding the bridge, as well as the corrosion resistance of the steel material itself. It is, therefore, important to evaluate the environment of a steel bridge and select a suitable steel material to secure the required anti-corrosion performance of the bridge. Nippon Steel & Sumitomo Metal has developed YOSOKU—a computer program that permits predicting the corrosion loss of various types of weathering steels at the planned site of construction without carrying out any exposure test. Formerly, importance was attached only to the airborne salt concentration as the major corrosive factor. On the other hand, YOSOKU considers not only the amount of airborne salt but also temperature, humidity, time of wetness, wind velocity, etc. as corrosive factors. It is utilized as a tool for judging the applicability of JIS-SMA and nickel-based high-performance weathering steels.

Concerning JIS-SMA, based on the results of exposure tests with shelter at 41 domestic bridges and amount of airborne salt measured inside the bridge girders in the three-party joint research mentioned earlier, regression analyses considering the influences of various corrosive factors were conducted to provide appropriate coefficients and mathematical equations for YOSOKU. For nickel-based high-performance weathering steels, also correlations with JIS-SMA have been established based on the results of exposure tests conducted at several different places.[12, 13] The applicability of YOSOKU has also been verified by exposure tests of several steel bridges other than the 41 bridges tested in the above joint research. In fact, it has been confirmed that the predicted corrosion loss curve agrees well with the measurement data.[20]

YOSOKU permits the prediction of the amount of long-term corrosion loss in shelter environment that is extremely corrosive. With the aim of confirming the reliability of YOSOKU, the results of corrosion loss prediction by YOSOKU were compared with the results of a horizontal exposure test conducted for five years from July of 2006 by shelter condition under the inner girder of the simulated bridge. The environmental conditions used in the comparative study were as follows. The amount of airborne salt is the measured value (0.036 mdd) [8] shown in Figs. 5 and 6; the meteorological factors are based on data supplied from Fushiki Meteorological Observatory nearest to the test site; and the amount of sulfur oxide is 0.15 mdd, decided considering the environment of the locality.[13] The results of prediction of long-term corrosion loss by YOSOKU and the results of the exposure test are shown in **Fig. 14**. The measurement data for both JIS-SMA and 3%Ni-added high-performance weathering steel fit within $\pm 2\sigma$ of the prediction curve, proving the validity of predicting the corrosion loss by YOSOKU.

4. Maintenance Management Technology

In recent years, in view of the aging social infrastructure, the mounting need to prepare against large-scale disasters, etc., the demand for the maintenance management technology of social infrastructure has become stronger than ever before. Concerning the existing bridges that play a pivotal role in the traffic network, there is growing demand for proper maintenance technologies to prolong their life and increase their durability. Regarding on the maintenance

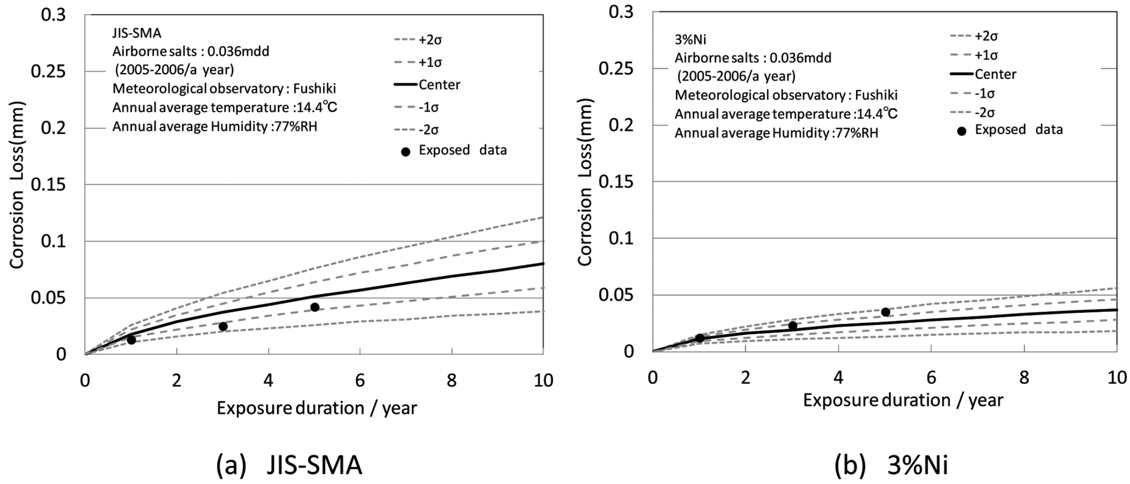

Fig. 14 Comparison of corrosion loss between forecasting curve and measured data

Fig. 15 Ion transfer resistance measurement (RST)

Fig. 16 Grinder with manmade diamond grains

Fig. 17 Example for repaired painting

technology of weathering steel bridges including nickel-based high-performance weathering steel, if any damage is detected by inspection, it is necessary to make suitable repair or reinforcement and thereby maintain their functions. Nippon Steel & Sumitomo Metal has been developing effective new methods relating inspection/diagnosis and repair/reinforcement of weathering steel bridges to achieve a "minimum maintenance" through realization of safe and secure bridge structures and prolongation of their life.

In the inspection/diagnosis of a weathering steel product, it has been a common practice to visually check the condition of rust formed on the steel surface. For that practice based on the appearance rating system,[20] it is necessary to directly and quantitatively examine the condition of formation of protective rust. To solve that problem, Nippon Steel & Sumitomo Metal has developed an instruments (RST) for measuring the ion transfer resistance of rust (**Fig. 15**). Nippon Steel & Sumitomo Metal has proposed a scheme for the quantitative judgment of the condition of rust formed on the steel surface by evaluating the ion transfer resistance and thickness of rust (see Fig. 8).[13–15] This technique is unique, in that it permits the quantitative determination of the condition of rust through an electrochemical analysis, rather than the subjective judgment based on visual check of the appearance. Registered in the New Technology Information System (NETIS) of the Ministry of Land, Infrastructure and Transport, it is a promising technology applicable as a tool for inspection (Reg. No. KT-110072-A).

For the repair of weathering steel bridges, various techniques have been also developed. What is considered especially important for weathering steel materials is how to deal with abnormal corrosion if it occurs. In general, even if abnormal corrosion, such as delamination rust or rust like fish scale, occurs on the surface of a weathering steel material, repair painting is unnecessary as long as the cause thereof can be eliminated. When the cause of corrosion (e.g., leak of water) cannot be completely eliminated, it is common practice to paint the abnormally corroded part as a means of repair. However, note that if the surface preparation before the repair painting is insufficient and the salt deposit remains on the steel surface, rust may occur under the paint film, causing the anticorrosion performance to be lost early. It has been indicated that rust caused by abnormal corrosion is so sticky that blasting it off takes much time and that salt deposited on the steel surface can hardly be removed.[21]

To solve the above problems, Nippon Steel & Sumitomo Metal has developed a grinder manmade diamond grains[22] (**Fig. 16**) that is capable of efficiently removing sticky rust from the surface of weathering steel plate and a zinc-rich paint[22] that displays good anticorrosion performance even if the concentration of salt deposit on the steel surface is higher than the conventional reference (50 mg/m^2). Based on the above achievements in technology development, a procedure for proper repair painting of weathering steel bridges has been proposed and put into practical use (**Fig. 17**).[21]

5. Conclusion

In this paper, we have described an example of the evaluation of secular changes of 3%Ni-added high-performance weathering steel in actual use, the validity of long-term corrosion loss prediction technology (YOSOKU) using actual exposure test data, and the development of technology for the maintenance of weathering steel bridges. Incidentally, Nippon Steel & Sumitomo Metal has recently developed and placed a new corrosion-resistant steel for painting cycle extension (CORSPACE™)[23, 24] into practical use for environments that are subject to so severe salt damage that even nickel-based high-performance weathering steels cannot be used there (**Fig. 18**).[25] We intend to continue pressing ahead with our research and development on both the hardware (steel products) and software (steel product application technology) to allow for the "minimum maintenance" of steel bridges.

Acknowledgments

We wish to express our heartfelt thanks to Japan Railway Construction, Transport and Technology Agency for their cooperation in the exposure test we carried out in the neighborhood of the elevated bridge of Hokuriku Shinkansen over the Hokuriku Highway.

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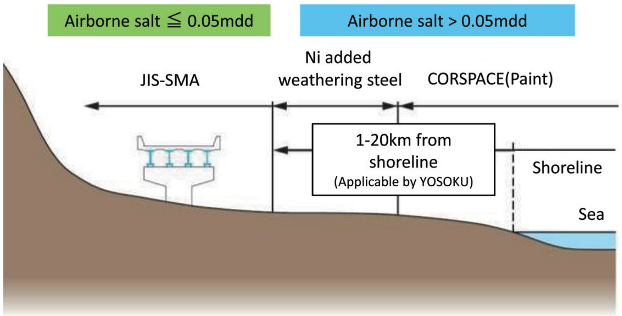

Fig. 18 Application image of various low alloy corrosion resistance steels

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Makoto NAGASAWA
Researcher
Plate & Shape Research Lab.
Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511


Mutsuto TANAKA
Senior Manager, Head of Dept.
Plate Products Technical Service & Solution Dept.
Plate Technology Div.
Plate Unit


Ryuichi ANDO
Senior Manager
Plate Products Technical Service & Solution Dept.
Plate Technology Div.
Plate Unit


Motohiro OKUSHIMA
Senior Manager, Head of Dept.
Plate Products Quality Management Dept.
Quality Management Div.
Nagoya Works


Yoshiyuki HARADA
Senior Researcher
Materials Reliability Research Lab.
Steel Research Laboratories


Masahide TAKAGI
Senior Manager
Bridge Products Engineering Dept.
Construction Products Development Div.
Construction Products Unit