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3% Ni-Advanced Weathering Steel and Its Applicability Assessing Method

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Abstract

As a method to assess applicability of 3% Ni-advanced weathering steel to unpainted structures, a computer software program for corrosion prediction was developed. Also, recently proposed minimum maintenance methods for unpainted structures, which are more elaborate than ever before, are also described systematically.

1. Introduction

Weathering steel has been applied to many structures beginning with bridges because of its unique and special characteristic of using rust to control rust. There are many examples of applying this function to steel structures and achieving great success in reducing the costs associated with maintenance. On the other hand, careless application in marine regions where there is much airborne salt has caused problems. In recent years, rust formations have been found indicating localized problems because of the effects of antifreeze agents being dispersed in inland regions. As representative of the minimum maintenance structure concept advocated by the Ministry of Construction, Public Works Research Institute, there is demand for weathering steel, surface treatment technologies and construction design methods that further reduce maintenance costs and allow for their actual use with certainty for ultra-long periods of time in structures of the future particularly with bridges.

There are great expectations for weathering steel technology development that realizes structures that are safe and that ensure that there is a minimum to the life cycle cost (LCC) as directed and as one type the 21st century's infrastructure for maintaining Japan's cost competitiveness with the nations of Asia. In order to promote the development of this technology, research was done into the phenomenon of corrosion of weathering steel at the Rust Chemistry Committee, Japan Society of Corrosion Engineering (JSCE). At the 132nd Corrosion Prevention Symposium which was held on June 25, 2001, a definition of *durable state* was presented[1]. Furthermore, discussions relating to the application of weathering steel have been advanced in Tokyo Institute of Technology's Science and Technology Research Body "Research Center for Urban Infrastructure." The fundamental recognition relating to the application of weathering steel was proposed in April of 2001[2].

These discussions were reflected when revising the Specification for Highway Bridges (the Japanese Roads and Bridges Policy Manual), the Commentary, I the Common Section, and II Steel Bridges Section (hereinafter referred to as the Roads and Bridges Policy Manual)[3] in March, 2002. In that manual, 'Chapter 5 Consideration of Durability' was added to make it mandatory for designs to consider the degradation of members over time for the realization of semi-permanent structures having low life cycle costs. Also, it is not possible to realize long term durability of structures simply with the materials and the designs. It is clarified in the Roads and Bridges Policy Manual to inspect whether the rust-proofing treatment is functioning appropriately, and to take the necessary steps such as repairing areas that are found to be defective. The radically different point with the conventional design standards manual is the increased freedom in selecting materials assuming that the performance of use is satisfied as is called for in the performance based designs. Specifically, as shown in **Fig. 1**, the three points of technologies including the selection of materials, inspections, and diagnoses, must advance as overall technical developments.

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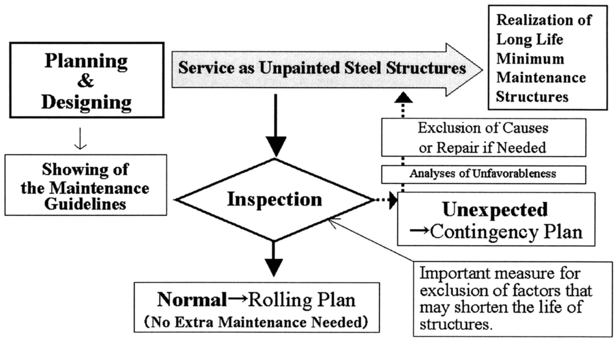

Fig. 1 System image of minimum maintenance bridge technologies for weathering steel

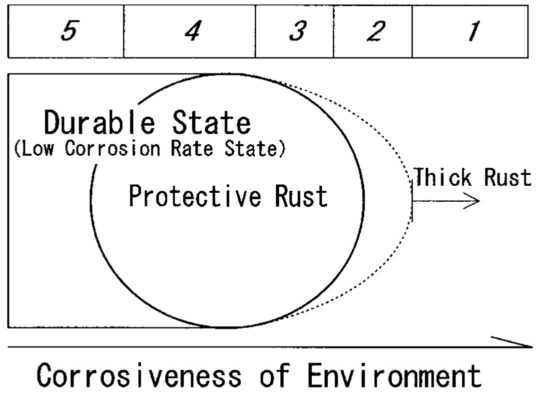

Fig. 2 Relationship between the durable state image and visual ratings of rust

2. Durable State of Weathering Steels

The term "*durable state*" is defined as state in which corrosion rate is low enough so that thick rust does not form. Here, the meaning of rust that is abnormal is layered rust. The rust that requires observation is scale-like rust. These are handled as signals that indicate that the corrosion rate of steel materials has increased. Based on the nationwide bridge exposure tests in 41 locations conducted by the Ministry of Construction, Public Works Research Institute, the Japan Association of Steel Bridge Construction, and the Kozai Club, it was judged that SMA weathering steel described in JIS G 3114 (hereinafter referred to as JIS-SMA weathering steel) can be used in environments estimated to maintain a degree of deterioration to within 0.3 mm on one side over 50 years. These environmental conditions are equivalent to an environment where airborne salt amounts are below 0.05 mg/dm^2/day[3]. If used within this range, the corrosion rate of weathering steel is low enough that the thick rusts described above will not be generated.

Recently, the period for design performance has been set to 100 years[3]. Therefore, in order to achieve that goal, the cumulative sliming amount is calculated to be 0.5 mm[4] when weathering steel is to be applied within the environmental limits. It is realistically impossible to expect that steel bridges having been applied with a general painting will not show some degree of corrosion on their surfaces at all over the period of time exceeding 100 years. The Roads and Bridges Policy Manual outlines the minimum thickness standard in consideration of corrosive environments, the manufacturing and the handling of steel during shipment. Thus, it is natural to interpret this to be a standard for the design or maintenance of any structure even if there is a degree of corrosion on the surface over a long period of time but that that corrosion does not lead to the end of life of the structure's load performance. If the degree of corrosion can be kept within this minute amount, it can also be said that it might be even more rational not to apply paint.

Nevertheless, regardless of whether a steel bridge is painted or unpainted, the steel materials surface will show some degree of corrosion over long period of time that exceeds 100 years. Therefore, by clarifying designs and maintenance control methods that consider this fact, bridge structures can be guaranteed for safety and certainty. In other words, it is possible to realize semi-permanent lives for unpainted weathering steel bridges, if materials selection, setting thicknesses, construction designs are adequate, and maintenance and control are executed for the environment of application.

Fig. 2 is a conceptual drawing to understand appearances of rust. The corrosion rate of weathering steel varies depending upon the severity of the corrosive environments. If the corrosive environment is mild, the corrosion rate is extremely slow. Therefore, rust is generated more slowly and the increase in a protective function is difficult to occur. However, considering long-term stability of the structure, the degree of sliming of the steel materials is extremely minute and is not considered to be a problem. If the severity of the corrosive environments is of a mid-severity, the alloy elements included in the weathering steel promote formation of rust having a highly protective function. This actually acts to reduce the corrosion rate over the years. The degree of corrosion over a long period of time can be maintained at a stable level for the structure.

Furthermore, if the environment is highly corrosive, rust that has this protective function is not generated. Thus, the corrosion rate increases causing the structure to be less able to withstand the environment as expected, and the abnormal rust is formed. If the weathering steel is in the durable state, the rate of corrosion is reduced. Therefore, the generating rate of new rust is equivalent or lower than the decomposition rate of old rust, so the rust does not thicken. **Fig. 3** will facilitate understanding of this concept. Because the rate of corrosion of the steel materials varies according to the severity of the corrosive environment and the degree of formation of protective rust,

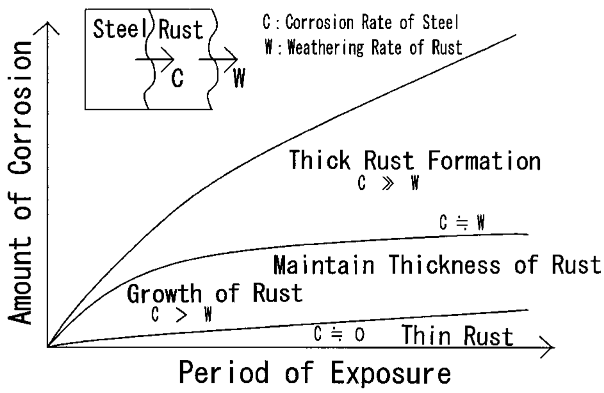

Fig. 3 Schematic interpretations for appearances and thicknesses of rusts relating to corrosion rates (balance between the rate of rust supplying and that of weathering dominates the appearance and thickness of rust.)

the thickness of the rust and the external appearance are transformed as shown in Fig. 3. Specifically, rust that forms on the surface functions as a sensor to indicate the rate of corrosion of the steel materials. The five grade rating method advocated by Japan Association of Steel Bridge Construction and Japan Iron and Steel Federation for the external appearance of rust, which is described below, is one of the ways for determining the rationale of corrosion rate based on the durable state concept depicted in Fig. 2.

Studies were conducted to expand the region for protective rust formations by the alloy component designs of advanced weathering steels[4] that has been commercialized domestically by the various steel manufacturers in Japan. Therefore, the limits for environments in which they are applied vary according to the alloy components.

3. 3% Ni-Advanced Weathering Steel with Increased Ability to Withstand Salt Damage

Research has been conducted relating to the limit of the environment where these advanced weathering steel was to be applied. Since this new weathering steel had increased ability to withstand salt damage, it was, at the outset of its commercialization, called a beach and ocean front weathering steel. However, from policies[5], directions in which the degree of corrosion to 0.5 mm on one side for 100 years are indicated. There are many cases in which airborne salt amounts become too high at narrow beaches or the ocean front. In order for customers not to be confused, the new steel materials including at least 0.4% nickel, which is the fundamental element[6] to increase the ability of this product to withstand salt, was named Ni containing Advanced Weathering Steel[5]. Nippon Steel Corporation was the world's first to develop and commercialize a new steel product that had 3% Ni and 0.4% Cu. Therefore, this product was named 3% Ni Advanced Weathering Steel. To Inherit conventional product code, this was often disclosed as 3% Ni Advanced Weathering Steel (coastal weathering steel) with the additional name in parentheses. The reason for adding Ni in the name of advanced weathering steel, was to identify this from another advanced weathering steel having a high P content that has been conventionally in use. According to the weathering the alloyed index (*V* value) as proposed by Miki et. al.[5], 3% Ni-advanced weathering steel has the highest weather ability among the same kind with *V*   1.55.

The stabilizing mechanism of 3% Ni advanced weathering steel rust was presented in a research paper[6] in the journal entitled "Zairyo-to Kankyo." The rust that indicates abnormalities (layered and peeling rust etc.) is generated because the reactive rate of corrosion is accelerated by a lowering of pH at rust and steel interface. Protective rust having highly environment shielding properties is formed by long-term exposure with conventional JIS-SMA weathering steel. In addition to that, the ion exchanging function of this protective rust is controlled by the increased amounts of nickel, thereby at the rust and steel interface, the Na^+ ions from the airborne salt is enriched so the 3% Ni-advanced weathering steel suppresses the lowering of pH at the corrosion interface.

Steel material design concept was proved by evaluation exposure tests conducted over nine years at the Chiba Kimitsu Wharf. **Fig. 4** shows a macro photograph a sectional view of the material exposed in the vertical direction without shelter as an example of the results. While the JIS-SMA weathering steel showed entire amount of metal steel was changed to layered rust, the 3% Ni advanced weathering steel retained almost all its metal. The results of the exposure test for those underneath a shelter also revealed meaningful differences in both. The conversion equation from the weathering alloy

Fig. 4 An example of cross sectional macro picture of exposed steels for the demonstration of alloy design concepts. The exposure site was located at 10 m from the sea shore at a wharf in Kimitsu City, Chiba, Japan, where conventional JIS-SMA and 3% Ni advanced weathering steels were vertically exposed without shelter for 9 years.

index *V* value disclosed in the research paper authored by Miki et.al[5] to the corrosion rate parameter was established using data from the series of sheltered exposure tests performed by Nippon Steel Corporation. Note that sheltered exposure test was devised to simulate inner girder condition where rust that indicates abnormalities tends to form easier than outer girder condition.

4. Method to Assess the Applicabitity of Ni Containing Advanced Weathering Steel

All matters in the world experience chemical reactions. Concrete, plastics, painted steel are not exceptions. Simply because protective rust has formed on the surface of weathering steel does not mean that further the chemical reaction of corrosion has stopped on the surface.

There are many methods described in the Roads and Bridges Policy Manual for preventing corrosion on steel materials. Examples of such methods include covering the surfaces, modifying the surface, electrochemical protection, or modifying the steel materials itself. Generally, corrosion of the steel material is prevented by forming a cover of some type over the steel surface, or suppressing corrosion to a certain degree. Therefore, with weathering steel it is necessary to use the corrosion of the steel materials itself by using the protective rust forming functions to suppress corrosion to a certain limit by thoroughly considering the corrosive environments around the structures. Specifically, it is a rule to use this within a range wherein rust which indicates abnormalities of the weathering structures does not form. As described above using the period for design performance which has been set to 100 years as a guide, this is equivalent to a degree of corrosion of 0.5 mm on one side[4, 5]. If conventional conforming specifications[3] are observed, it is rational to determine whether to apply this to the 3% Ni-advanced weathering steel in the same way.

To begin with, an assessment of permanent weather ability starts with the conditions of the environment of the structure being considered at the planning or design stage. Subsequently, measurements and calculations are made with regard to the degree of corrosion of the steel surface that could occur during the stated period of time, and these calculations are then applied to the structure itself. Specifically, the bridge structure design and manufacturing are conducted in consideration[3] of its degradation in overtime. Maintenance control policies including this process have been determined, which should be notified to personnel who are in charge of controlling and managing structures. This made it possible to realize a safe and secure minimum maintenance for bridges. If one understands technical theory for permanent steel bridges deeper, this methodology becomes ever more embodied. Depending on the value judgments of the bridge construction project, there will be little worry about corrosion on one side that is less than 0.5 mm over 100 years. Thus, it is possible to propose plans that ensure the safety and the security of bridge structures by selecting advanced weathering materials such as steel materials, surface treatment agents etc. in the design process, and by using the appropriate anti-corrosion means such as setting margins for corrosion. Through these preservation technologies that assume those strategies for longevity, it is possible to reduce the costs associated with bridge maintenance even further. For that reason, the basic tools are technologies to predict the degree of corrosion of steel materials.

The equation $Y = AX^B$ is known to express the degree of corrosion overtime of weathering steel with Y (mm) as thickness loss and number of years of X. However, because the method to estimate the values of A and B which are the corrosion rate parameters, was unknown. So far, they have been obtained through the recurrence of the exposure test results over approximately 10 years. Thus, an estimating calculation algorithm was developed for the A and B values. By inputting the conditions of the environment for the structure and information relating to the alloy components, it becomes possible to predict the degree of corrosion for any weathering steel without conducting exposure tests. Based on the above mentioned algorism, simulation software for predicting the degree of corrosion was developed[7] as can be seen in **Fig. 5**.

Specialists in Nippon Steel who are well versed in weathering steel select adequate condition among a variety of conditions. Therefore this software was used to assess the applicability of 3% Ni-advanced weathering steel on the actual structures. This software simulation system can also be used to envision the effects of anti-corrosion treatment such as surface treatment applications or painting and repainting on to the corrosion losses in the future. The selection of materials in the planning and design stages is the most important issue to assess in relation to achieving long-term minimum maintenance. The technology for predicting the degree of corrosion dramatically increases reliability to the weathering steel bridge structures and eliminates corrosion damage through reckless applications. The authors believe this technique will contribute to enable a lighter load on taxpayers by minimizing the life cycle costs.

5. Inspecting and Diagnosing Durability

By accurately selecting the appropriate materials and setting the appropriate thickness of the steel plates in consideration of the structure and the environment at the planning stage, long-term durability of the weathering bridge structures can almost be achieved. However, it is possible that problems occur because of a variety of issues that involve the several processes and issues that can occur while in use. There can also be unexpected changes in the environment. Therefore, periodic inspections are necessary. Unlike inorganic materials, steel materials cannot produce chemical deterioration of the mother metals by the atmospheric environment. Therefore, only maintaining the state of the surface is enough to ensure long life of the structures.

Fig. 6 introduces proposed standards for judgments[8] of the external observation method for rust which is a basis for the concept of durable state. This was analyzed, assessed and proposed by Working

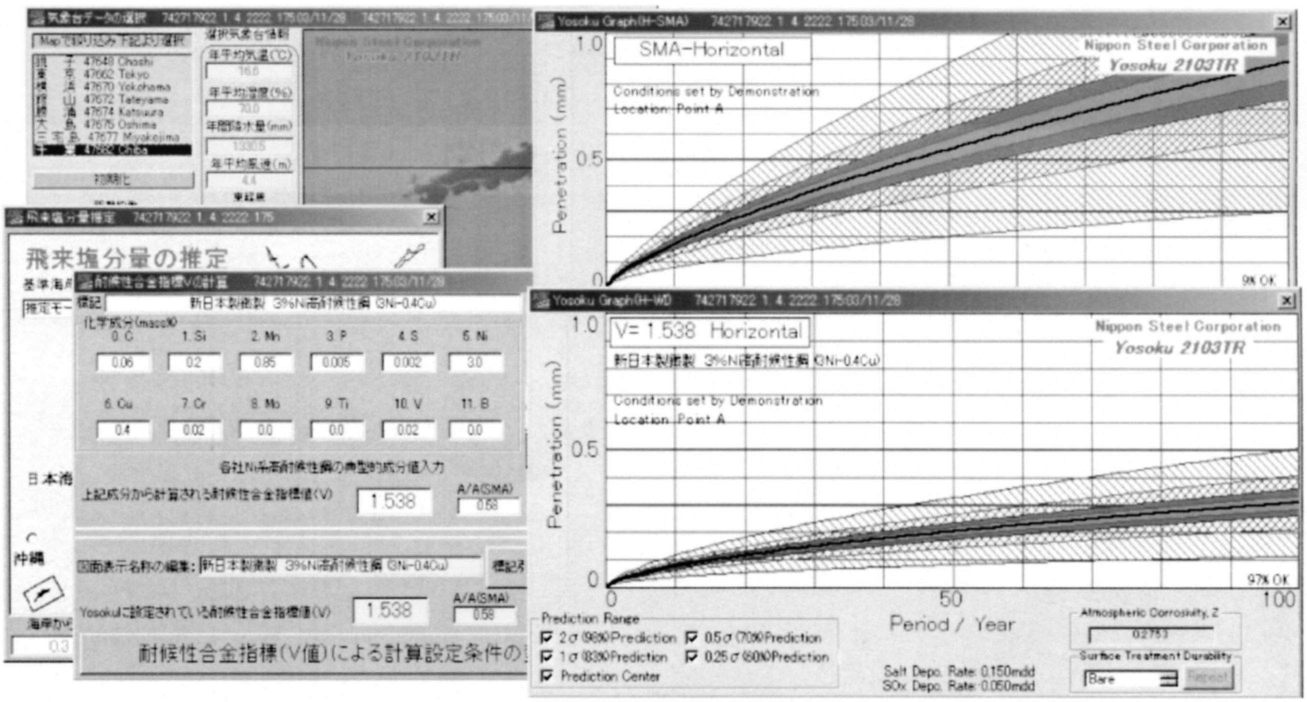

Fig. 5 Examples of computer aided corrosion prediction schemes estimated from meteorological data, simulated air born salt deposition rate, alloy composition of steels, etc.

Rating	Status	Typical Appearance	Rust Thickness
5	Normal	Thin rust due to very low corrosion rate.	less than ca.200μm
4		Attached rust particles of less than ca.1mm in horizontal average size.	less than ca.400μm
3		Attached rust particles of ca.1mm – 5mm in horizontal average size.	
2	Observation needed	Rust like fish scale.	from ca.400μm to ca. 800μm
1	Unexpected	Thick and/or delaminated rust.	More than ca. 800μm

Status can be judged after 9 years of exposure, confirming that there is no trace for delaminated rust to have fallen off.

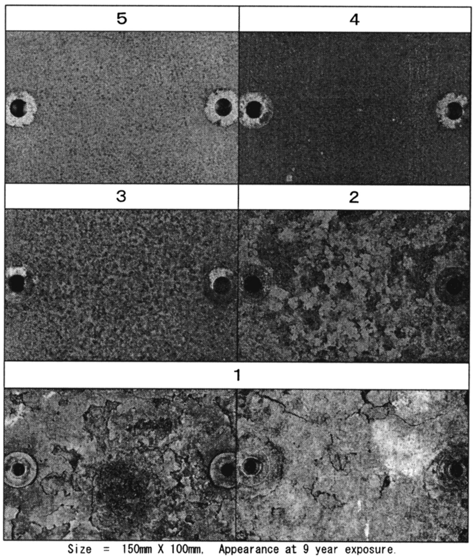

Fig. 6 Ratings for visual inspection method relating to the rust thickness ranges proposed by Japan Association of Steel Bridge Construction and Japan Iron and Steel Federation, together with exposed test samples typical to the each rating category.

Group for Durability Design Methods Using Weathering Steels of Bridge Technology Committee in the Japan Iron and Steel Federation as requested by Division of Unpainted Steel Bridge in Japan Association of Steel Bridge Construction. Visual inspection of the external appearance is the foundation. A rust thickness meter is used as a supplement to inspect whether the subject is not below the value point 2. If the subject is an evaluation point of 3 or above after the ninth year, it is considered that weathering steel members are in *durable state*. A judgment standards proposal is being reviewed even for other methods such as the ion transfer resistance method which increases judgment accuracy, the electric chemical potential measuring method, and the quantitative X-ray analysis method. This is being proposed[8] by Working Group for Durability Design Methods Using Weathering Steels of Bridge Technology Committee in the Japan Iron and Steel Federation. Of these, the ion transfer resistance method was developed independently by Nippon Steel Corporation and put into use as a so-called Rust State Tester (RST) and can be applied in a wide variety of locations. This has contributed to the increased reliability of diagnoses[9]. RST has been commercialized by the Nittetsu Anti-corrosion Co., Ltd. These inspection and diagnosing methods can also be applied to the Ni-advanced weathering steel.

6. Repair Technologies

Finding out the rust indicating abnormalities in the inspections does not mean that the bridge life is over. Also, in consideration of the life cycle costs, finding out the rust indicating abnormalities should not be considered as a failure to apply weathering steel. However, it is certain that the conditions of the environment at least that portion exceed the environmental limits of the application. Unless the appropriate corrosion measures are taken, or unless the cause of the corrosion is eliminated, the permanence of bridges will be hindered in regions where rust that indicates abnormalities is being generated. There already are examples of repair using the conventional JIS-SMA materials. Therefore, repairs are possible. More efficient and effective repair technologies are being developed by linking with industries having high technical levels by the several research groups and committee activities that have been organized by the Japanese Society for Steel Construction, Japan Association of Steel Bridge Construction, and the Japan Iron and Steel Foundation. If problems also arise in Ni-advanced weathering steel, the same methods can be applied.

7. Application to Actual Structures

The 3% Ni-advanced weathering steel has been applied to the Hokuriku bullet train railway over the Hokuriku highway in 1998 (see **Fig. 7**); and the Nahari Bridge for the Tosa Kuroshio railways (see **Fig. 8**). It has also been applied to bridge structures linking the island of Honshu to the Kobe airport. An interesting application as can be seen in **Fig. 9**, is to the sculpture entitled ‘Stairway to Kuh’ which is a monument in a park near the entrance of the Yamagata highway Tsuruoka interchange. Approximately 17,000 t of the 3% Ni-advanced weathering steel have been shipped as of March, of 2004. The total amount of Ni-advanced weathering steel shipped by the domestic steel manufacturers is approximately 27,000 t. This is evidence of the expanded efforts being made by the government, academia and regular citizens toward minimizing maintenance and its costs.

Fig. 7 A bridge for Hokuriku Bullet Train Railway over Hokuriku High Way to which 3% Ni advanced weathering steel is applied for the first time in the world, where the pipe and ship bottom like shape designs of viaducts are devised not to accumulate deposited salt, together with the application of weather resistant surface treatment called RusCor N, to realize minimum maintenance features.

Fig. 8 Nahari Bridge for Tosa Kuroshio Railways, Kochi, Japan where 3% Ni advanced weathering steel is applied without any surface treatment.

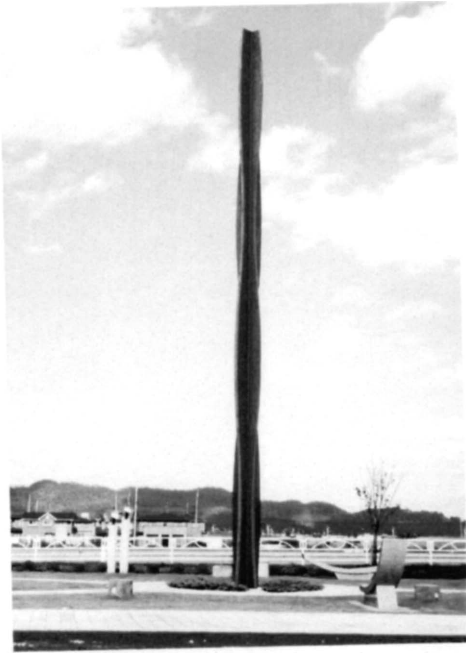

Fig. 9 A monument, created by Mr. Minoru Togashi, the sculptor, with height of 21m and weight of 40t made of solid 3% Ni advanced weathering steel named "Stairway to Kuh (空)", installed in a park near Tsuruoka Interchange of Yamagata High Way. Note that standing for sky or naught in daily use, the Chinese character " 空 " in Buddhism sutra symbolizes the concept for the ultimate origin of everything in the universe.

8. Conclusions

Once a bridge structure has been established, it becomes a part of the capital of society which cannot be easily replaced. Therefore, there are demands for ultra-long service lives of such structures, which are sometimes called semi-permanent structures. It was not possible to have thorough discussions with regard to the handling of the degree of deterioration accumulated over a long period time on the surface of steel. With the revision of the Specification of Highway Bridges of March, 2002, developments have been made with regard to alter long term permanent technologies for steel bridge structures, and therefore it has been possible to undertake realistic discussions and to take more specific efforts to refresh the technologies. Now, steel bridges are planned, designed, manufactured and maintained with careful consideration being given to the degradation of its members over time. Technical theories that ensure bridge users of their safety and security with the minimum life cycle costs are being developed. Thorough efforts are being taken for anti-corrosion materials and weathering steel application technologies along with Ni-advanced weathering steel, degree of deterioration and corrosion predicting technologies. These will dramatically reduce the load on taxpayers, and increase international competition.

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There have been numerous investigations and discussions with experts from the government, academia and manufacturing with regard to technologies to ensure long-term durability of steel bridges with minimal maintenance. The authors wish to extend their deep gratitude for the contributions of all the members of the research groups and committees that have been associated with this paper.

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