LCC Evaluation Method regarding the Anticorrosion of Steel Bridge in a Highly Corrosive Environment

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Under-coat corrosion progresses very rapidly after the repainting of steel railway bridges that have been in use for long periods of time in highly corrosive environments. It is therefore important to use high-quality base conditioning methods. However, these methods can be very costly. Consequently, it is essential to establish not only a method for selecting steel bridges that require high quality repainting, but also to find repainting methods that factor in life-cycle costs (LCC evaluation method). This paper examines a method for selecting steel bridges for LCC evaluation, and then describes an LCC evaluation method that takes into account the cost of surface preparation. Based on a trial calculation of the LCC for models of steel bridges with typically found structures, an appropriate repainting method was proposed.

Keywords: anticorrosion, life-cycle costing, corrosion beneath the painting, steel structure.

1. Introduction

On steel railway bridges that have been in service for many years in highly corrosive environments, under-coat corrosion can occasionally begin earlier than anticipated after a repainting cycle (Fig. 1). This can be caused by any residual rust that is not eliminated during base conditioning prior to repainting. Higher-quality, therefore more costly, base conditioning techniques such as blast cleaning need to be used for steel railway bridges built in highly corrosive environments. In addition, amid the growing need in recent years for more labor-saving and more efficient maintenance of steel railway bridges, repainting techniques that offer protection for longer periods are in greater demand. These arguments suggest that, to optimize the anticorrosion maintenance of steel railway bridges, repainting-related life cycle costing (LCC) needs to be studied.

In the study covered by this paper that aimed to propose an appropriate repainting method for steel railway bridges built in highly corrosive environments, related feasibility and costs of applying the identified methods, including appropriate base conditioning, were evaluated and calculated. Based on this initial work, a practical LCC method for repainting was proposed and the method was then applied to model steel bridges with typical configurations to identify an appropriate repainting method.

For steel railway bridges that do not experience under-coat corrosion such as those built in low-corrosion environments, demand for high-quality base conditioning is negligible. Therefore, those bridges were excluded from evaluations on the applicability of the LCC method. Thus, prior to examining an appropriate LCC method, an suitable method first had to be found to identify steel railway bridges to which the LCC method would be applied.

2. Method for selecting steel railway bridges for evaluation using LCC method

2.1 Evaluation using corroded-under-coat steel plates

In selecting steel railway bridges for evaluation using the LCC method, it is necessary to evaluate the progress in under-coat corrosion on members that have been painted on a base still carrying residual rust. It is difficult to analyze progress in under-coat corrosion through only a limited number of environmental factors when it is in fact affected by numerous external elements including temperature and time of wetness.

To overcome this obstacle for the purposes of the study, small test pieces were therefore painted on substrates still carrying rust residues (hereafter “corroded-under-coat steel plates”) which were then attached to steel railway bridge members and exposed, to develop a method for estimating progress in under-coat corrosion.

To validate the method, exposure tests were conducted at a public test station, on members of steel railway bridges that had already experienced under-coat corrosion as well as on cutouts of steel railway bridge members placed in an ultra-low corrosion environment.

Fig.1 An example of under-coat corrosion
2.2 Outline of corroded-under-coat steel plates

2.2.1 Preparation of corroded-under-coat steel plates

Cold rolled steel plates (sandblasted on both sides) produced according to JIS G 3101 were used for the tests. The steel plates measured H 150 mm x L 70 mm x T 3.2 mm. The plates affixed to steel railway bridges were resized to H 75 mm x L 70 mm x T 3.2 mm before being attached to the bridge members to help prevent them from falling. To ensure a uniform state of corrosion among the steel plates, they were continuously sprayed with neutral salt water according to the indoor accelerated corrosion test method [1]. The concentration of salt water was set to either 0.01 wt% or 0.05 wt%. The plates were sprayed for either 168 hours or 840 hours. Following the spraying, the rust that had formed on the plates was loosely removed with wire brushes.

2.2.2 Outline of painting process

Paint System T (three high-build coats of modified epoxy resin + a high-build top coat of polyurethane resin), which is widely used for steel railway bridges, was used for the coating of the steel plates.

2.3 Exposure test at public test station

Pre-prepared corroded-under-coat steel plates and bare steel plates were installed at the Japan Weathering Test Center’s Miyakojima Exposure Test and Research Center. The steel plates were installed according to JIS Z 2381 and exposed from April to November 2015.

Figure 2 shows the ratio of blistered area on the corroded-under-coat steel plates to months of exposure. As shown in the figure, blisters initially spread rapidly and then slowly. Corroded-under-coat steel plates exposed to the salt water spraying process had areas with different rust properties. Some areas contained chloride ions in the rust which can cause bulging soon after application of the coating [2]. Based on this finding, it was presumed that in the exposure tests the initial blistering must have occurred in areas on the steel plates with corresponding properties, while later the other blisters spread slowly.

In the next step, the corroded-under-coat steel plates were evaluated for corrosion. The extent of the corrosion on the bare steel plates was determined from the average reduction in plate thickness (erosion) calculated by the difference in plate mass before and after rust removal. In the case of the corroded-under-coat steel plates on which it was not possible to remove the rust from beneath the coat of paint, the extent of corrosion was evaluated through increase in plate mass, which should correspond to the rust formed in the corrosion process [3]. Erosion of the bare steel plates is shown in Fig.3. Changes in mass of the Paint System T-coated test pieces is shown in Fig.4.

As rust provides protection against environmental factors that contribute to corrosion, the extent of corrosion of the bare steel plates can be approximated from:

\[ y = a \times x^b \]  \hspace{1cm} (1)

Where \( y \) is the extent of corrosion, and \( a \) and \( b \) : corrosion rate parameters; and \( x \) : the number of years of exposure.

In the exposure test as well, the power regression curve obtained by the least-squares method and measurements showed similarities. On the other hand, the rate of increase in the mass of corroded-under-coat steel plates rose with months of exposure. One contributing factor to this was the appearance of very small defects in the paint coating as under-coat corrosion progressed, reducing the surface protection performance of paint against external corrosion factors. Also, in under-coat corrosion, hydrous ferric oxides, a type of crystalline iron oxide that corrodes products, contributes to this reduction reaction which can be represented as:

\[ 8\text{FeOOH} + \text{Fe}^{2+} + 2\text{e}^- \rightarrow 3\text{Fe}_2\text{O}_3 + 4\text{H}_2\text{O} \]  \hspace{1cm} (2)

In the reaction, water molecules desorb, shrinking the volume of rust while creating numerous voids. As a result, it is thought that moisture and oxygen pass more easily through the corroded products.

The findings described above show that the corroded-
under-coat steel plates and bare steel plates went through different corrosion processes and that the former type of steel plates should be used rather than the latter type of steel plates for the evaluation of progress in under-coat corrosion of steel bridges.

2.4 Exposure test on steel railway bridges and cut-out members

Test pieces were attached to three steel railway bridges (Bridge A, Bridge B and Bridge C) that had experienced localized heavy corrosion and were selected for the application of the proposed LCC method. Test pieces were also attached to cutouts of disused girders set in an ultra-low corrosion environment on the premises of RTRI’s Kunitachi Institute. Figure 5 shows the locations of the bridges and the Kunitachi Institute. As shown in Fig.6, test pieces were attached to the outer web faces of I-section, or main girders, and the bottom faces of the girders’ lower flanges using adhesive tape and thermo-conductive sheets. After exposure of about one year, the ratios of blistered areas on the test pieces attached to the corroded-under-coat steel plates and the extent of erosion on the test pieces attached to the bare steel plates, were calculated.

The results are shown in Table 1. With the cutouts, there was no significant difference in the extent of corrosion among the test pieces attached to the various locations. With the bridges A, B and C, however, the location of the worst corrosion was different on the bare and corroded-under-coat steel plates. Among the bare steel plates, the largest patches of erosion were observed on those attached to the bottom faces of the lower flanges, where they could not be rain-washed and where sea salt tended to form and accumulate. Among the corroded-under-coat steel plates: on the cutouts, the highest ratio of blistered area was observed on the test pieces attached to the web faces of the I-section girders facing south; and on bridges A, B and C, the highest ratio of blistered area was observed on the test pieces attached to

![Fig. 5 Locations of bridges and disused girders](image)

![Fig. 6 Locations of attached test pieces](image)

![Fig. 7 Locations of attached test pieces](image)

Table 1 Locations of the attached test pieces

| Locations of the attached test pieces | Bridge A | Bridge B | Bridge C | Disused girders |
|---------------------------------------|---------|---------|----------|----------------|
| Erosion of bare steel plates          | x       | y       | z        |                |
| x: Outer web faces facing south       | 0.04 mm | 0.11 mm | 0.04 mm  | 0.02 mm        |
| y: Outer web faces facing north       | 0.06 mm | 0.16 mm | 0.13 mm  | 0.02 mm        |
| z: Disused girders (at the Kunitachi Institute) | 0.02 mm | 0.10 mm | 0.10 mm  | 0.01 mm        |
| Area ratio of blisters of the corroded-under-coat steel plates | x | y | z |        |
| x: Lower flanges                      | 15%     | 20%     | 7%       |                |
| y: Outer web faces facing north       | 10%     | 10%     | 10%      |                |
| z: Disused girders (at the Kunitachi Institute) | 1%     | 10%     | 7%       |                |

*Cases A and B had corrosive conditions for the steel plates of the corroded-under-coat steel plates. Case A: Concentration of salt water was 0.01 wt%, Case B: Concentration of salt water was 0.05 wt%.

Figure 7 shows the relationship between the highest ratios of blistered areas on the corroded-under-coat steel plates and the extent of erosion on the bare steel plates. The extent of corrosion and the ratios of blistered areas on the test pieces attached to the disused girders were much lower than those on the test pieces attached to the steel railway bridges, exhibiting the reality of the corrosion suffered by the structural members to which they were attached. The relationship between the ratios of blistered areas on the corroded-under-coat steel plates and the extent of erosion on the bare steel plates was not linear. This is probably because, as shown in Fig.2, the rate of increase in the ratios of blistered areas tended to taper. The corroded-under-coat steel plates showed similar ratios of blistered areas on all the steel railway bridges to which they were attached; 15% and above for those prepared with a 0.01 wt% conc. of salt water and 35% and above for those prepared with a 0.05 wt% conc. of salt water. These figures can be used as thresholds for classifying steel railway bridges into those likely to develop under-coat corrosion and those that were not likely to.

Based on the above, it was decided that the method using corroded-under-coat steel plates was an appropriate method for selecting steel railway bridges to which the LCC method could be applied.
3. Practical LCC method for repainting

3.1 Evaluation equations and parameters

Life cycle costing for repainting a steel railway bridge can be calculated from the related cost of the operation and repainting intervals. The costs of a repainting cycle can be calculated from:

\[ C = (1 + d) (C_i + C_r + C_p + C_s + C_d) \]  

(3)

Where \( C \) is the total cost of the repainting cycle, and 
\( C_i \) : cost of base conditioning; 
\( C_r \) : repainting cost; 
\( C_p \) : cost of paint; 
\( C_s \) : cost of scaffolding; 
\( C_d \) : costs of safety measures etc.; 
\( d \) : ratio of various expenses.

LCC involves adding up future costs and therefore handles costs over different time sequences. A cost method is often used to convert future costs into corresponding present values. The cost method can be represented by:

\[ C_{total} = \sum_{t=1}^{\infty} \frac{C_t}{(1+r)^t} \]  

(4)

Where \( t \) is the repainting interval, and 
\( C_t \) : repainting cost \( t \) years from now; and 
\( r \) : discount rate.

In this study, a discount rate of 4\% was used based on a previous paper [5].

3.2 Application to model steel bridges

The LCCs for repainting the model steel bridges were calculated using the equations described in the previous section, for cases where hand and power tools were used and cases where blasting was employed, to select an appropriate repainting method. The calculation exercise involved the cost of paint, base conditioning, repainting and scaffolding, each of which can vary significantly depending on what specific option is chosen.

3.2.1 Model steel bridges

Three model steel bridges were used, each representing a widely used steel railway bridge type and modeled after an existing railway steel bridge of that type. The three bridge types were a deck-plate girder bridge, a through-plate girder bridge and a through-truss bridge. Table 2 shows the painted and scaffolded areas on each model steel bridge.

### Table 2  Painted and scaffolded areas on each model steel bridge

| Structure type | Deck-plate girder | Through-plate girder | Through truss |
|---------------|------------------|---------------------|--------------|
| Width (m)     | 1.4              | 5.8                 | 4.7          |
| Length (m)    | 20               | 26                  | 64           |

| Painted area (m²) | Above the track | Below the track |  |
|-------------------|-----------------|-----------------|---|
|                  | 20              | 100             | 1200 |
| Scaffolded area (m²) | 210           | 750             | 1000 |

**The ratio of area with exposed steel (%)**

| Class | Class 1 | Class 2 | Class 3 |
|-------|---------|---------|---------|
| Base conditioning method | Hand tools and power tools | Blast cleaning |
| Rust | Still left | Removed almost completely |
| Paint system | T | J |
| Repainting interval (years) | 5 | 15 |
| **Ratio of area with exposed steel (%)** | 25 | 100* |

* Class 1 used for subsequent repainting cycles.
** The ratio of area with exposed steel on members when repainting was set to 1% for subsequent cycles.

- **Class 1: Base conditioning using power tools**

This is one of several widely used methods, although rust is still left on heavily rusted steel members. The Paint System T was used. The exposure test results described in
Section 2.4 suggest that with this method under-coat corrosion may appear after about one year. However, because of economic considerations, the repainting interval was set to five years. This means corrosion will have time to progress on the members, which will therefore need repair and reinforcement in future. Based on the film degradation status applied to a 5-year repainting interval, the ratio of exposed steel area on a member requiring base reconditioning was set to 25%.

- **Class 2: Base conditioning using power tools to completely remove rust**

  During the first repainting cycle, corrosion products were removed almost completely using power tools. During subsequent repainting cycles, the Class 1 method was used. The Class 2 method was used initially with a view to completely removing rust to stifle under-coat corrosion progression. Based on the speed at which this method is applied, base conditioning using the Class 2 approach is estimated to cost about 20 times as much as Class 1.

  The repainting interval for the Paint System J was set to 15 years based on the results of a survey on steel railway bridges which were painted using this system at the time of construction [6].

- **Class 3: Base conditioning by blasting**

  Overall blasting is performed with the ratio of exposed steel on members set to 100%. The Paint System J was used and the repainting interval was set to 15 years. As rust is removed almost completely with this method, second and subsequent repainting cycles only require small areas to be treated. Therefore, the ratio of exposed steel on members during repainting cycles was set to the minimum value (1%) specified in the 2005 version of the painting and design manual for steel structures [7]. The scaffolding cost was set to the same level in the other class methods because corrosion was expected over the whole steel bridge.

### 3.2.4 Life cycle costings for model steel bridges

Table 4 shows unit costings for repainting the model steel bridges.

Table 4  Unit costings for repainting model steel bridges

| Class   | Structure type* | Gd | Gt | Tt | Gd | Gt | Tt | Gd | Gt | Tt |
|---------|----------------|----|----|----|----|----|----|----|----|----|
| Cost of paint (thousand yen/m²) | 1.1 | 1.8 | 2.1 |
| Cost of repainting and base conditioning (thousand yen/m²) | 2.8 | 51.8 | 51.8 |
| Cost of scaffolding (thousand yen/m²) | 3.6 | 4.3 | 4.7 |

*Gd : Deck-plate girder, Gt : Through-plate girder, Tt : Through truss

Fig. 8  Cumulative cost of repainting over 100-years based on unit costings

4. Conclusion

With the aim of proposing an repainting method that optimizes LCC for steel railway bridges built in highly corrosive environments, first, a series of different methods were examined to find the one that would best identify steel railway bridges on which practical LCC evaluations should be conducted, and secondly a review of repainting methods was made to find which one would be the most efficient. The key findings of this work are outlined below:

1) A method was proposed for selecting steel bridges on which an LCC review should be conducted. In the method, the progression rate of steel bridge corrosion was determined based on the extent of under-coat blisters on corroded-under-coat steel plates left exposed at various locations on steel railway bridge members.

2) A method to determine life cycle repainting costs was proposed that factors in the expected serviceable life of paint systems and cost of the method.

3) The proposed life cycle costing method was applied to model bridges. It was found that base conditioning by means of blasting can reduce life cycle costs for repainting to justifiable levels if the bridge is to be put in service for more than 10 to 35 years depending on the configuration of the bridge.

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