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Durability Grading of Steel Bridge Facilities Considering the Degradation of Steel and Coating

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Abstract: **--Steel bridges are extremely vulnerable to corrosion that needs continuous and proper maintenance. In order to achieve efficient and economic maintenance, the execution of rational condition evaluation as well as repair and strengthening should be addressed in terms of safety and durability to prevent the occurrence of serious structural defect. The present study proposes a methodology that evaluates quantitatively the condition of coated steel using a degradation model and, based on the so-obtained results, evaluates quantitatively the durable performance of the steel bridge facilities by means of durability grades. Considering that the factors causing the degradation of coated steel are the rust of steel itself or the flaking, checking, blistering or chalking of the coating, the degradation model is derived from the relationship between the service life and the total degradation score obtained from the condition evaluation related to each of these factors. In addition, criteria for the grade classification assessing the durability grade of coated steel are derived based upon the degradation model.**

Index Terms: — Rust and flaking of coated steel member, Degradation model, Durability grading of steel bridge, Maintenance.

I. INTRODUCTION

In absence of adequate maintenance, structures of which members are made of steel like steel bridges may experience loss of both durability and stability due to corrosion. For vessels and marine structures, it is well known that environmental factors like chloride influence significantly the corrosion. However, the corrosion and corrosion-induced loss of performance for road facilities subject to deicing agents in urban or mountainous areas or subject to severe pollution in industrial zones have been comparatively ignored to date [1]. In general, the strength of steel reduces by 5% to 10% for every 1% of corroded material and it is known that steel becomes useless when corrosion has progressed by more than 5% on both sides of the material.

Accordingly, when a corroded member is used as main structural member or joint without proper repair and strengthening, very high risk is taken for the safety of the structure [2]. In a steel bridge for example, the welded parts, the bolted parts, the parts subjected to repeated loading, and the parts playing the role of structural anode by collecting the rainwater or condensation are exposed to relatively higher risk of local corrosion compared to the other parts. Especially, the joints require special attention to be paid because local corrosion may affect the overall safety of the structure [3].

Documents published by the American FHWA reported that most of the corrosion occurring in inland bridges was caused by deicing salts and that the bridges exposed to low or practically no salinity could withstand 100 years whereas those exposed to deicing salts in a long-term see their lifespan reduced to 15 to 18 years [4, 5]. The corrosion of rebar and steel member in 15% of the 583,000 bridges in USA was reported to be the primary cause of defect and, the direct and indirect costs required for the corresponding repair, strengthening and replacement reach annually 8 billion USD and 83 billion USD, respectively [6]. Extensive research has been conducted on the effect of the chlorides in reinforced concrete structures but there is relatively less studies on the same topic for steel structures like steel bridges, which translates in rather inadequate measures for preventing corrosion. For example, Korea has prepared an Inspection Guideline [8] and method for the condition evaluation and the grading of reinforced concrete members based on research results on the degree of rebar corrosion according to the chloride content inside reinforced concrete members. This Guideline also proposes grading evaluation criteria for steel structures according to the degree of deterioration but uses mostly safety-related evaluation parameters. In most cases, it is difficult to scheme appropriate repair and strengthening schedule for rational condition evaluation and maintaining the durability because the durability-related evaluation indices like the flaking, checking, blistering and chalking of the coating are not considered and also because of the absence of degradation

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model [7].
Consequently, the present study intends to propose a methodology that evaluates quantitatively the condition of coated steel using degradation model and, based on the so-obtained results, evaluates quantitatively the durable performance of the steel bridge facilities by means of durability grades. This study hereafter also intends to contribute to the establishment of the efficient maintenance planning of steel structure facilities by applying the analysis results of long-term data to the proposed degradation model and durability evaluation method. To that goal, the degradation state of 59 steel bridges scattered all over the country is rated using a quantitative score considering degradation factors including the rust, i.e. the surfacial corrosion, of steel and, the flaking, checking, blistering or chalking of the coating as evaluation indices. The relationship between the computed score and the service life of the coating is obtained by curve fitting to propose a degradation model. Finally, the method determining the durability grade of the coated steel is suggested based on this degradation model.

II. DURABILITY EVALUATION INDEX AND DEGRADATION MODEL

A. Durability Evaluation Index

The existing Korean inspection guideline for facilities [8] considers several indices for the condition evaluation of steel structures such as the flaking area of the coating, the rusted surficial area and the damaged cross sectional area of steel member caused by rust [7-9]. However, as shown in Table 1, the following five types of degradation are distinguished for coated steel: rust of steel and, flaking, checking, blistering and chalking of coating. A quantitative evaluation related to these indices is thus necessary to conduct the evaluation in term of the durability performance. Here, chalking is the phenomenon in which one or more constituents of the coating decompose and can be graded, for example, using the evaluation criteria of the current KS M ISO 4628-6 [10]. Moreover, rust, flaking, checking and blistering can be graded using KS M ISO 4628-3, KS M ISO 4628-5, KS M ISO 4628-4 and KS M ISO 4628-2 [10], respectively. In the present study, the criteria of the Korean Industrial Standards are used for the example but the criteria of other foreign standards can be used as well. The grading of each index can be determined by measuring the degradation area and density. In addition, the total degradation evaluation score of the coated steel can be obtained by summing the computed grading score of each index factored by a weight considering its importance as shown in Table 2.

Table 1 Degradation Evaluation Indices of Coated Steel [7, 9, 10]

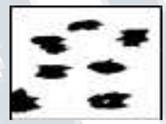
Evaluation indices	Degradation pattern	Actual examples
Rust		
Flaking		
Checking		
Blistering		
Chalking		

Table 2 Example of computation process of total degradation score

Inspection	Grade classification	Scoring	Total Score
Rust 	a	5^{*1}	10
Flaking 	a	2	
Checking 	a	1	

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Blistering 	a	1.5	
Chalking 	a	0.5	

*1) Considering the ratio, Rust:Flaking: Checking; Blistering: Chalking = 50:20:10:15:5, 10 X (50/100) = 5

Tables 3 to 5 show examples of grading criteria for each of the indices. Table 6 lists the score per grade for each index needed to compute the grading score (damage score, DS) from the field inspection and grading results for each index. Here, the scores defined to be 10 points for grade a, 20 points for grade b, 40 points for grade c and 70 points for grade d refer to the “grading criteria according to damage score range” proposed in the existing Korean inspection guideline for facilities [8] as shown in Table 7. The scoring is partially adjusted for the convenience of computation. Moreover, the total score per grade is defined as the point attributed to each evaluation index by assigning the rating ratio of 50:20:10:15:5 to rust, flaking, checking, blistering and chalking, respectively [7, 9]. The differentiation of the score per index by using such weighting ratio considers the fact that each of the degradation factor has a different effect on the durability. The rating ratio was determined by performing a survey among experts in the field of maintenance.

Table 3 Example of grading criteria for rust, flaking and checking of coated steel member

Grade	Rust area	Flaking area	Checking area
a[*1]	Less than 0.05%	Less than 0.1%	Less than 0.05%
b[*2]	0.05% ~ less than 0.5%	0.1% ~ less than 0.3%	0.05% ~ less than 0.5%
c[*3]	0.5% ~ less than 5.0%	0.3% ~ less than 5.0%	0.5% ~ less than 10.0%
d[*4]	5.0% ~	5.0% ~	10.0% ~

*1: No visible defect or presence of defect but with neglectable level, *2: Slight defect but anti-corrosion performance of coating maintained in other parts, *3: Clear defect, *4: Defect spread practically all over the external surface

Table 4 Example of grading criteria for blistering of coating

Size and area of blistering	Less than 0.05%	0.05% ~ less than 0.5%	0.5% ~ less than 5.0%	5.0% ~
Less than visible with normal visual acuity	a	a	b	c
Clearly visible with normal visual acuity (less than 0.5 mm)	a	b	c	d
0.5 ~ less than 5 mm	b	c	c	d
More5 mm	c	d	d	d

Table 5 Example of grading criteria for chalking of coating

Grade	Chalking
a	No change compared to early inspection. No residue of falling powder on test tape.
b	Slight whitening compared to early inspection. Slight adhesion of falling powder on test tape.
c	Significant whitening compared to early inspection. Adhesion of falling powder on test tape.
d	Remarkable whitening compared to early inspection. Large adhesion of falling powder on test tape.

Table 6 Example of grading criteria for chalking of coating

Grade	Rust	Flaking	Checking	Blistering	Chalking	Total score
a	5	2	1	1.5	0.5	10
b	10	4	2	3	1	20
c	20	8	4	6	2	40
d	35	14	7	10.5	3.5	70

Table 7 Grading criteria according to damage score (DS) range

Grading	A grade	B grade	C grade	D grade	E grade
DS range	0 ≤ x < 0.13	0.13 ≤ x < 0.26	0.26 ≤ x < 0.49	0.49 ≤ x < 0.79	0.79 ≤ x

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B. Degradation Model

The degradation model can be used to determine the durability grade by deciding the region of the degradation model to which the degradation state of the coated steel member inspected on field belongs. In this study, the degradation model is obtained by representing the relation between the total degradation score related to each of the evaluation indices (rust of steel and, flaking, checking, blistering and chalking of coating) and the service life of the coating. The data of 39 steel bridge facilities [11] and the field inspection data of 20 steel bridges [7] were used to derive the degradation model. Fig. 1 presents the inspection process and degradation state of one of the 20 latter steel bridges

(a) Inspection process *(b) Flaking of coating*
(c) Rust of steel *(d) Checking of coating*

Fig. 1 Degradation inspection process and example of degradation state [7]

The surveyed field data are evaluated according to the grading criteria per index. The derived relationship between the total score and the service life of the coating is expressed by the averaged equation (2). The averaged equation can be formulated either by an exponential curve or a cubic polynomial curve but, referring to a previous literature [11], this study uses the exponential formulation that is widely adopted to express the degradation model. The constants of the exponential formulation are determined by regression analysis. The lower bound equation (1) and upper bound equation (3) are the results of the statistical analysis of the data distribution. These equations include the degradation progress state of the different types of coating. By statistical theory, most of the surveyed degradation data lie between the lower and upper bound curves. Referring to this in-between region, the speed of degradation can be assessed. The degradation model plotted in Fig. 2 presents the lower bound and upper bound of the degradation curve for facilities exposed to atmospheric conditions. The degree of degradation can be specified quantitatively by determining the region of the degradation model to which the state of the coated steel member inspected on field belongs. The durability grade can also be determined based on this degradation model. Moreover, the speed of degradation and the future degree of degradation can also be predicted provided that data has been collected during several years for the facility at hand.

$$\text{Lower bound } y = 0.579e^{\frac{x}{7.066}} \quad (1)$$

$$\text{Average } y = 1.263e^{\frac{x}{5.173}} \quad (2)$$

$$\text{Upper bound } y = 2.754e^{\frac{x}{4.080}} \quad (3)$$

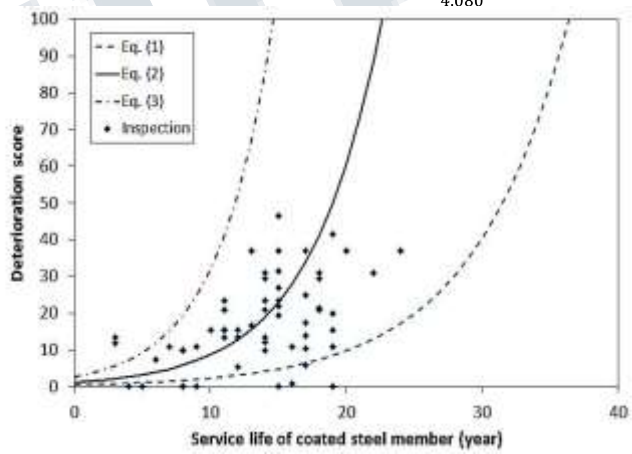

Fig. 2 Deterioration model for coated steel member in atmospheric environment

The degradation model of Fig. 2 was computed using the inspection data gathered for various types of painting system. Attention should thus be paid to the fact that the actual degradation evaluation results of a specific painting system will lie within the region described by the upper bound curve and the lower bound curve. For chlorinated rubber paint, the speed of degradation is relatively higher than that of heavy anticorrosive paint. This example is illustrated in Fig. 3, which distinguishes the inspection data of the 39 bridges using extensively chlorinated rubber paint and the 20 bridges using heavy anticorrosive paint. It appears that, when heavy anticorrosive paint featured by relatively better performance is used, the total degradation score is comparatively lower for the same service life of the coating. Even if it is recommended to apply the degradation model for the painting system directly used on the facility, such specific model cannot be applied because it is difficult to acquire data due to negligent maintenance generally accompanying the extended service life of the facility. Accordingly, the pattern of the degradation model shown in Fig. 2 can be meaningfully exploited to establish evaluation criteria that can be applied in practice by the inspector for the whole stock of steel bridge facilities using various types of painting system.

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This study obtained the degradation model of coated steel considering five types of degradation: rust of steel and, flaking, checking, blistering and chalking of coating. However, it is often difficult to distinguish the degree of degradation related to the checking, blistering and chalking of coating according to the field condition and the inspector. In most cases, rust and flaking can be found out and measured easily by any inspector. Accordingly, it can be interesting to verify how the evaluation results would change by assuming a situation where evaluation is done using only rust and flaking. Fig. 4 compares the degradation curve obtained using the 5 evaluation indices and that obtained using only two indices that are rust and flaking. In view of Fig. 4(a) comparing the degradation trend curves, there is no noticeable difference for the bridges with service life shorter than 15 years. However, for older bridges with longer service life, the absence of the evaluation results for checking, blistering and chalking tends to provide more satisfactory state evaluation than the actual one due to the lowering of the degradation trend curve. Moreover, the comparison of the upper bound and lower bound curves of the degradation shown in Fig. 4(b) reveals similar tendency

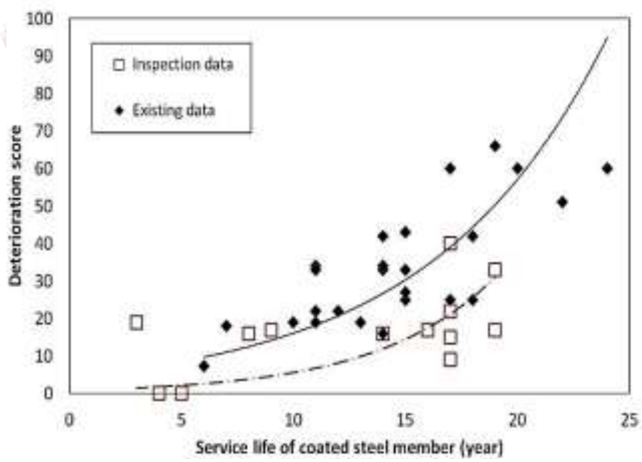
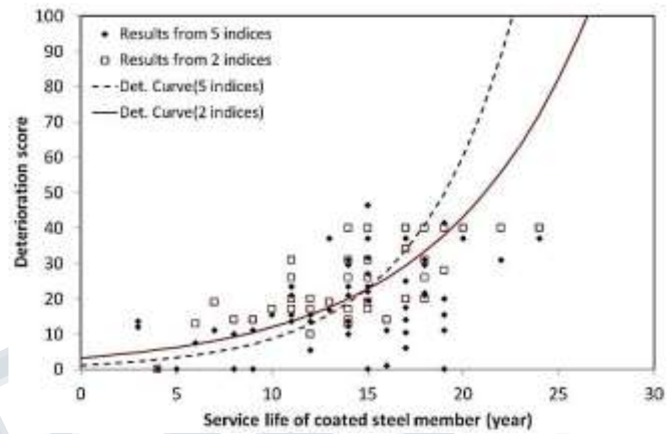
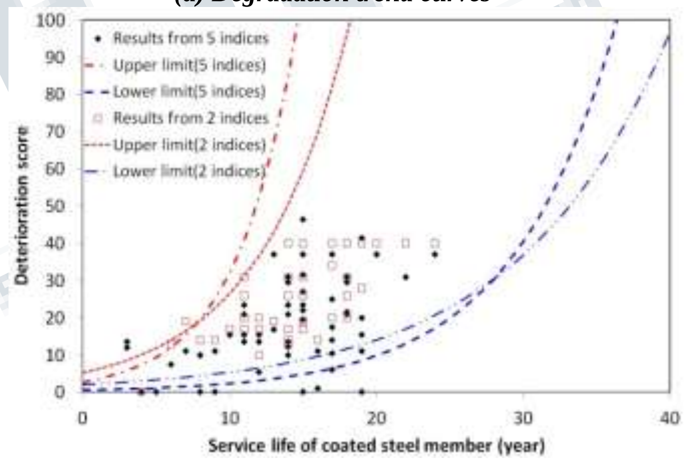


Fig. 3 Comparison of degradation models (chlorinated rubber paint and heavy anticorrosive paint)



(a) Degradation trend curves



(b) Upper bound and lower bound degradation curve

Fig. 4 Comparison of degradation model (5 indices versus 2 indices)

Even if slightly different curves can be obtained according to the considered indices, the inclusion of the rust of steel and flaking of coating, which are the most influencing factors on the degradation progress, can represent effectively the overall tendency. However, the following case should be considered when applying the grading method based on the degradation model obtained using only rust and flaking. In a situation where it is necessary to assess if the degradation speed of the inspected bridge is faster or slower than the normal speed, attention should be paid in the assessment when the total degradation score lies near the lower bound or the upper bound curve. Especially, when the total degradation score falls near the upper bound curve, it is recommended to implement maintenance with shorter period in order to maintain the durable performance.

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A. Method for the Determination of the Durability Grade for Coated Steel

The degradation level of the bridge member for each evaluation index (rust of steel and, flaking, checking, blistering and chalking of coating) was scored according to the determined degradation grade and these scores were summed up to give the total degradation score enabling to evaluate the durable performance of coated steel. Various indices can be considered for the evaluation of the durable performance of steel such as environmental factors including the salinity and the sulfur dioxide concentration in the atmosphere but only indices representing the degradation state within the scope of this study are adopted here. In addition, since the change of the member section thickness caused by severe corrosion is more related to the safety than the durability, this index is discarded and only the area of the rust developed at the surface of the member is included. The change of the member section thickness should be addressed separately through safety inspection and subsequent appropriate measures.

The durability grade can be determined using the degradation model expressing the relation between the total degradation score and the service life of the painting system. This method is illustrated in Table 8 and Fig. 5. The range of the total score for grade classification in Table 8 refers to the "grading criteria according to damage score range" proposed in the existing Korean inspection guideline for facilities [8] similarly to Table 7. As shown in Fig. 5, the grades from a to c correspond respectively to stage I with slow degradation speed, stage II with normal degradation speed and stage III with fast degradation speed. Grade d corresponds to a state at which degradation has already progressed significantly and requiring repair within the shortest delay. It is therefore meaningless to link grade d with the degradation speed. The determination of the durability grade using Fig. 5 is done by identifying the zone of the degradation model to which the relation between the total degradation score and the service life of the painting system belongs. Here, this grade can be exploited to determine the location and number of inspection during the next inspection if the degradation speed is indicated together with the resulting durability grade. The classification system is limited to 4 grades from a to d because grade e related to another index (for example, corrosion thickness) means that we have reached a situation requiring the cease of exploitation and the implementation of immediate repair due to the rust and the coating degradation.

Table 8 Criteria for deciding the durability grade of coated steel

Grade	Range of total score	Definition of grade
a	Less than 13	Loss of durable performance can be ignored
b	13 ~ less than 26	Slight defect but satisfactory state in other parts
c	26 ~ less than 49	Partial repair required for member with defect
d	49 ~	Extensive repair required

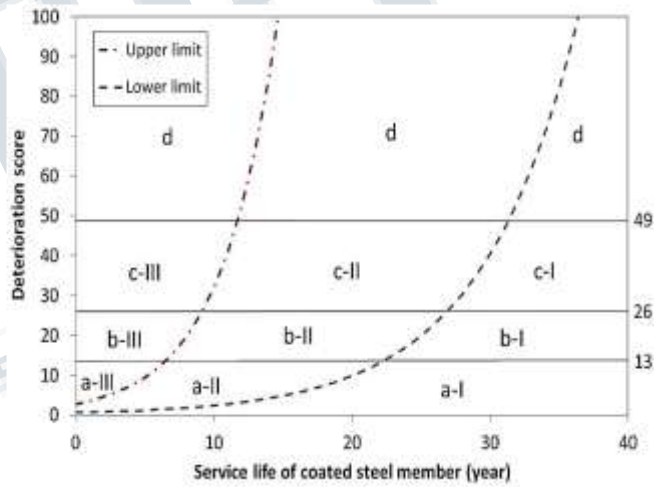

Fig. 5 Durability grade classification of coated steel member based on degradation model

II. CONCLUSION

The bridge chapter of the existing Korean guideline for precise safety diagnosis of infrastructures prescribes the inspector to compute the damage score and determine the state grade by visual inspection of the flaking of coating, the corroded area of steel and the corrosion depth for evaluating the state of the steel member. This approach may provide unreliable evaluation results because it mixes indices evaluating the durability and the safety and does not consider the various degradation factors of coated steel. Moreover, this method does not consider a degradation model involving service life time, which means that the evaluation results may not be fully exploitable for determining the degradation speed and establishing relevant maintenance schedule. Consequently, the present study presented a methodology that evaluates quantitatively the condition of coated steel using a degradation model and, based on the so-obtained scores, evaluates the durable performance of the steel bridge facilities by means of durability grades. In details, the rust of steel and the flaking, checking, blistering and chalking of the coating were considered as the degradation factors of coated steel, and the relation between the total degradation score obtained from the condition evaluation for each of these factors and the service life of the painting system was used to derive the degradation model. Since this degradation model includes the time factor, the degradation condition can be evaluated quantitatively. Based on the degradation model, a grade classification system was derived to assess the durability grade of the coated steel. Note that the degradation model can be used by the inspector to establish practical evaluation criteria since the model involved a steel bridge stock using various types of painting system. The proposed methodology for determining the durability grade reflects partially the current Korean inspection guideline for facilities [8]. This methodology will contribute to the establishment of the efficient maintenance planning of steel structure facilities by applying the analysis results of long-term data to the proposed degradation model and durability evaluation method.

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