Internet Journal of Society for Social Management Systems Vol.10 Issue 1 sms15-8426
ISSN: 2432-552X
ORIGINAL ARTICLE

Comprehensive Deterioration Prediction with Panel Unit Data of RC Slabs on Expressway Bridge

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Abstract**:** In order to manage some of infrastructures efficiently, periodical visual inspection has been carried out and record data of strange condition in infrastructures have been accumulated over the years. With the record data, methods of the statistical deterioration prediction has been investigated and developed. While the deterioration of RC slabs for steel bridge in an expressway has been predicted with the Markov deterioration hazard model using the deterioration evaluation with the free lime method, it is only data of macroscopic unit (span unit data) that deterioration prediction is carried out with. The result of the deterioration prediction with span unit data is used the decision of an inspection and a repair is made with each span unit in RC slabs. However, in actual maintenance, there are cases that the deterioration speeds of each panel differ. In addition, the inherent information is lacked in each panel the result of the deterioration prediction with span unit data. In this study, the authors are targeting the record data of inspection units (panel unit data) of RC slabs on an expressway bridge, and analyzes of deterioration factors in detail. Furthermore, in order to make the decision with the result of deterioration prediction using panel unit data, the authors propose the method to calculate expected life span in the evaluation of span unit data using state distribution of panel unit data.

Keywords RC slabs, panel unit data, Markov deterioration hazard model, state distribution

1. INTRODUCTION

The ministerial ordinance for partially amending the Ordinance for Enforcement of the Road Act (enforced on July 1, 2014) obliged bridge administrators to visually inspect the bridges they manage at close range every 5 years. On the other hand, as bridges are deteriorating rapidly, there are many bridges that should be inspected more frequently. In the inspection manual, inspection period is evenly established as a target on all bridges whose length is 2.0 meter and over. Detailed standards do not exist for the environment and structure conditions in which individual bridges is placed. However, some bridges greatly deteriorate, so that, visually inspection every 5 years is not sufficient. Bridge administrators are required to manage bridges efficiently and reasonably in accordance with environmental and structural condition. Currently, due to the progress of deterioration, the increase in the size of the vehicle and the increase in the traffic volume, the environment surrounding Japanese bridges is under more pitiless conditions than originally assumed design. The instances of replacing the RC slabs because of significant deterioration have been increasing year by year. In the near future, it is suggested that the planning of large-scale repair and

Received: 2015.09.15 / Accepted: 2016.01.20

renovation is needed. Bridge is one of the important structure that supports civil infrastructures in Japan. In the future, in order to perform efficient inspections and repairs, it is essential to grasp more detailed deterioration tendencies based on the usage environment and structural classification of the bridge.

In the maintenance of social infrastructure, a number of studies has been carried out in order to practice asset management such as the deterioration prediction and the life cycle cost analysis using statistical techniques. Also, regarding management of RC slabs, statistical deterioration prediction using Markov deterioration hazard model has been implemented. However, in the previous study, the deterioration prediction used span unit data in order to the making decisions of maintenance in span unit. For the efficient maintenance, it is required to conduct the deterioration factor analysis and the deterioration prediction with panel unit data. By using panel unit data, this study enables to plan the appropriate maintenance considering the environmental and structural deterioration factor.

Under the awareness of those problems in this study, first, the authors analyze the deterioration factors with panel unit data of RC slabs on expressway bridge managed by West Nippon Expressway Company Ltd. (hereinafter, NEXCO West) The result of analyses clarifies the characteristics of RC slab panel that is necessary to manage preferentially. Furthermore, using the soundness distribution that is obtained in estimation with panel unit data, the authors evaluate deterioration of span.

2. THE BASIC IDEA OF THIS STUDY

2.1 Actual Situation of Maintenance of the Bridge RC slabs

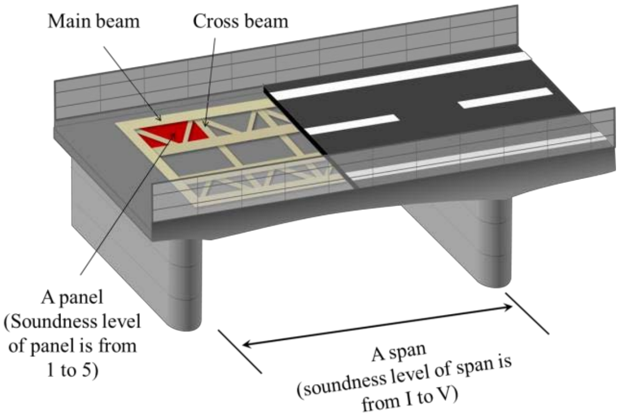

Figure 1. The composition of RC slabs

In July 2014, road law enforcement rules were revised by Japanese Ministry of Land, Infrastructure, Transport and Tourism. It is defined the following periodic inspection; “A Bridge whose length is over 2.0m must be carried out visual inspection once every five years.” However, it is important for management companies and local governments that manage such bridges to maintain efficient under the recent finance reduction. It is possible to be difficult to carry out the inspection once every five years for all bridges. On the other hand, in the highways and national roads, inspections have been carried out in less frequency than once every five years for a number of bridges the deterioration of that has progressed. In fact, the authors confirmed some bridges that were carried out inspections in once a few years in this study. Furthermore, it is not guaranteed that the obligation of the inspection once every five years is adopted permanently and there is a possibility that the determination of flexible measures in accordance with the various situations. Therefore, in order to maintain the bridges effectively, it is important to evaluate the deterioration status in detail and to decide contents and frequency of the inspections according to the deterioration state.

Recently, it is required to prepare the large scale repair and update project for progressing the deterioration of RC slabs on highway constructed in high economic growth period. Therefore, it is necessary to classify the RC slabs to manage

Table 1. The deterioration evaluation of a RC slab panel

<table>
<tr><th>Deterioration state of panel</th><th>Soundness level of panel</th><th colspan="2">The condition of a RC slab panel</th></tr>
<tr><td>E</td><td>1</td><td colspan="2">There is not a free lime or a cracking in over two directions.</td></tr>
<tr><td>D</td><td>2</td><td colspan="2">There are both a free lime and one a cracking.
There are cracklings in two directions without a free lime.</td></tr>
<tr><td>C</td><td>3</td><td colspan="2">There are both of free limes and cracklings in two directions and the one’s interval of them is over 50cm.
There are cracklings in two directions without a free lime and the interval of them is under 50cm.
A panel satisfies a condition of soundness level 2 and the deterioration of it progresses rapidly.</td></tr>
<tr><td rowspan="2">B</td><td rowspan="2">4</td><td>An ordinary part</td><td>There are both of free limes and cracklings in two directions, both of intervals of them are under 50cm, and the color of them is white.
A panel satisfies a condition of soundness level 3 and the deterioration of it progresses rapidly.</td></tr>
<tr><td>A part on a joint</td><td>There are both of free limes and cracklings in construction seams and the color of them is white.</td></tr>
<tr><td rowspan="2">A</td><td rowspan="2">5</td><td>An ordinary part</td><td>There are both of free limes and cracklings in two directions, both of intervals of them are under 50cm, and the free limes are discolored by the muddy water and the rust juice.
A panel satisfies a condition of soundness level 4 and the deterioration of it progresses rapidly.</td></tr>
<tr><td>A part on a joint</td><td>There are both of free limes and cracklings in construction seams and the construction seams are discolored by the muddy water and the rust juice.</td></tr>
</table>

preferentially. Currently, individual spans are evaluated in a deterioration degree and the manager prioritizes the repair and update based on the result of a deterioration degree. However, in order to grasping and analyzing the deterioration state and trend of RC slabs in detail, it is important that the individual panels in each of spans are grasped and analyzed.

In this study, the authors analyze the deterioration factors with panel unit data of RC slabs for the purpose of detailed evaluating the deterioration status of RC slabs. Then, using the result of evaluation with panel unit data, the authors perform the analysis according to the deterioration degree evaluation at the span units.

2.2 Configuration of RC slab and evaluation method of deterioration

Figure 1 shows the configuration of RC slab. The basic unit is panel such as the red portion surrounded

Table 2. Condition state and damage degree criterion of each span

Condition state	Condition of slab	Base of judge
I	There is damage of more than “D” in less than 30% of the slab.	There is a little damage. Partial repair and reinforcement are necessary.
II	There is damage of more than “D” in more than 30% of the slab.	There is a little damage. Repair and reinforcement are necessary in appropriate time.
III	There is damage of more than “D” in more than 40% of the slab.	The damage is becoming large. Repair and reinforcement are necessary in appropriate time.
IV	There is damage of more than “B” in more than 30% of the slab.	The damage is remarkable. Repair and reinforcement are necessary immediately.
V	There is damage of more than “B” in more than 40% of the slab.	The damage is remarkable. Urgent repair and reinforcement are necessary.

by the main girder and lateral digit and panel unit data of the deterioration information is obtained by the periodic inspection. In NEXCO West, the deterioration degree evaluation using the free lime method has been carried out. In the free lime method, occurrence of free lime and rust juice is focused on through the visual inspection from low side of the slab. According to the degree of the deterioration, the deterioration state of the panel is classified in 5 stage from E to A as shown in Table 1. E is assumed a state in which any damage is not observed, and A is assumed a significantly deteriorated state. On the other hand, the decision making in the practice such a repair is done in a span between adjacent piers as the smallest unit. Figure 1 shows that a span is composed of a plurality of panels and the soundness level of the span is determined according to the proportion of the soundness level of individual panels composing of a span. Soundness level of span is represented by Roman numerals. Soundness level I is the healthiest and V is a state that the deterioration is progressed significantly in. A span reached to soundness level 5 is required urgent repair. In NEXCO West, decisions such as repair scale and repair time is made with the result of the span determination. Table 2 shows a method of determining determine the soundness level of span in NEXCO West. In previous studies, the deterioration prediction has been implemented with span unit data. In this study, the authors implement the deterioration prediction with panel unit data, and then, the soundness level of span is estimated with the result of the deterioration prediction of panel. The utility of this study is followed; 1) the quantification of the deterioration progress of the individual panel, 2) the detail deterioration prediction of span in consideration of deterioration factor that differs in panel unit, 3) the support of a flexible response for changing the method to determine the soundness level of span.

3. Statistical Deterioration Prediction Technique

3.1 Markov deterioration hazard model

The authors represented the deterioration process of the RC slab panel using a Markov chain model. Markov deterioration hazard model used in this study is non aggregated model estimated by using the inspection data and the Markov transition probability of the Markov chain model is expressed by exponential hazard model. Therefore, there is a remarkable feature that the intervals of inspection need not be constant to estimate the model. The detail of the model is ceded to the bibliography and an overview of the model is explained in this section.

The hazard rate λ_i defined the deterioration speed of the panel at the state i ($i=1,\ldots,I-1$) is followed using the vector of estimation parameters $\boldsymbol{\beta}_i=(\beta_{i,0},\ldots,\beta_{i,n})$ and the vector of the deterioration factor $\bar{\boldsymbol{x}}=(1,\bar{x}_1,\ldots,\bar{x}_n)$;

$$\lambda_i = \exp(\bar{\boldsymbol{x}}\boldsymbol{\beta}_i') \quad (i=1,\cdots,I-1) \qquad (1)$$

n is the number of deterioration factor and the apostrophe is expressed the transpose operation. Markov transition probability $\pi_{ij}(z)$ changed the soundness level from i to j depends only on the hazard function λ_i and inspection interval z. Therefore, Markov transition probability $\pi_{ij}(z)$ is estimated without the inspection time τ_i when the soundness level i is obtained and the time $\tau_j=\tau_i+z$ when the soundness level $j(\geqq i)$ is obtained. Using the hazard function λ_i, the Markov transition probability is$\pi_{ij}(z)$($i=1,\ldots,I-1$;$j=i,\ldots,I$) expressed;

$$\pi_{ij}(z)=\sum_{m=i}^{j}\prod_{s=i}^{m-1}\frac{\lambda_s}{\lambda_s-\lambda_m}\prod_{s=m}^{j-1}\frac{\lambda_s}{\lambda_{s+1}-\lambda_m}\exp(-\lambda_m z)$$

$$(i=1,\cdots,I-1;\ j=i+1\cdots,I) \qquad (2)$$

However, as conventions,

$$\begin{cases}\prod_{s=i}^{m-1}\dfrac{\lambda_s}{\lambda_s-\lambda_m}=1 & \text{(at the time } m=i\text{)}\\ \prod_{s=m}^{j-1}\dfrac{\lambda_s}{\lambda_{s+1}-\lambda_m}=1 & \text{(at the time } m=j\text{)}\end{cases}$$

The characteristics of the Markov transition probability led to$\pi_{ij}=0(i>j)$, $\pi_{II}=1$. In addition, a maximum likelihood method is used to estimate the Markov deterioration hazard model.

3.2 Calculation of the expected life span of the unit

The soundness level of span is expressed using the soundness distribution with panel unit data. Therefore, the authors estimate the soundness distribution of panel with the Markov chain model to represent the deterioration process of panel and determine the expected life of span.

It is assumed that the time t_g that is elapsed the time g from the period of time t_0 when the service is started. The state vector $\mathbf{s}_p(t_g)=(s_{p,1}(t_g),\ldots, s_{p,I}(t_g))$ representing the deterioration distribution of the panel p ($p=1,\ldots,P$) at the time t_g is expressed using the state vector $\mathbf{s}_p(t_0)=(1,0,\ldots,0)$ at the time t_0 and the Markov transition probability matrix $\boldsymbol{\Pi}_p(g)$ that is composed of the Markov transition probability $\pi_{ij,p}(g)$.

$$\mathbf{s}_p(t_g)=\mathbf{s}_p(t_0)\boldsymbol{\Pi}_p(g) \qquad (3)$$

When the soundness level r of span is defined as the proportion of panels whose soundness level are over i_r is over A_r%, the expected lifetime L_r from the time starting service to the time when the soundness level reaches r is follows;

$$L_r=\arg\max_{t_g}\left\{t_g \mid \sum_{p=1}^{P}\sum_{i=i_r}^{I} s^{p,i}(t_g)\times(100|P)\leq A_r\right\} \qquad (5)$$

As above, it is possible to calculate the expected lifetime of span using the Markov transition probability of soundness of panel.

4. Case Study

4.1 Application case of data specifications

First, in this study, the authors analyze the deterioration factor of RC slabs targeting the steel bridges on expressway in NEXCO West with the Markov deterioration hazard model. This study is focused on future large-scale maintenance plan, and the authors extracted bridges in which the deterioration progress likely to be included in the repair plan. Specifically, the authors extracted the bridges with condition state in span unit are III, IV and V (67 bridges 99 spans), and the bridges that the replacement construction of the RC slabs has been performed in the past or scheduled (29 bridges 191 stations). In addition, for the extracted 290 spans, the authors obtained the deterioration state evaluation data of the panel units from a record of the inspection from the current or just before the replacement. The authors assumed that the RC slabs of the bridges in service start time are health and don’t progress the deterioration, and inspection data has been recorded as deterioration state E, in other words, soundness level 1. Soundness level 5 is control limits on the maintenance.

As a result, the total number of sample data was 13,803. Based on these data, Markov deterioration model is estimated. The authors considered following the characteristic variables as the deterioration factors: 1) the presence or absence of inherent salt at the time of construction, 2) whether or not the cumulative spray volume of antifreeze is 1000 t/km or more, 3) whether or not the large traveling lane of large vehicles, 4) the presence or absence of ASR, 5) minimum oblique angle, and 6) span length of RC slabs. The authors conducted *t* test to select the characteristic variables, and determined the characteristic variables to be statistically significant, if *t* value is above 1.96. In addition, conducting a study from the practical side, the authors adopted the following the characteristic variables as the deterioration factors: the presence or absence of inherent salt at the time of construction, whether or not the cumulative spray volume of antifreeze is 1000 t/km or more, whether or not the large traveling lane of large vehicles, and the presence or absence of alkali silica reaction (ASR).

4.2 Estimation results

The authors examined the estimation results upon the characteristic variables individually considered through the expected deterioration path.

First, it is focused on the presence or absence of inherent salt at the time of construction. It is one of the causes of salt damage deterioration, and there are many bridges including the inherent salt at the time of construction before 1986 when the amount of chloride was regulated by Standard Specification for Concrete Structures. In this case study, 79 spans have inherent salt at the time of construction. If there are inherent salt during construction, it is considered that the progress of deterioration due to salt damage is increased. The presence or absence of inherent salt was judged as a guide to 1.2kg/m^2 or more by the salinity survey. Figure 2 shows the estimation results in the case of adopting the presence of endogenous salt explanatory variables during construction. In Figure 2, the vertical axis is expressed soundness in the panel unit, and the horizontal axis is expressed elapsed year. The panel unit that includes inherent salt have expected lifetime of approximately 60.3 years, and that doesn’t include inherent salt have expected lifetime of approximately 99.1 years.

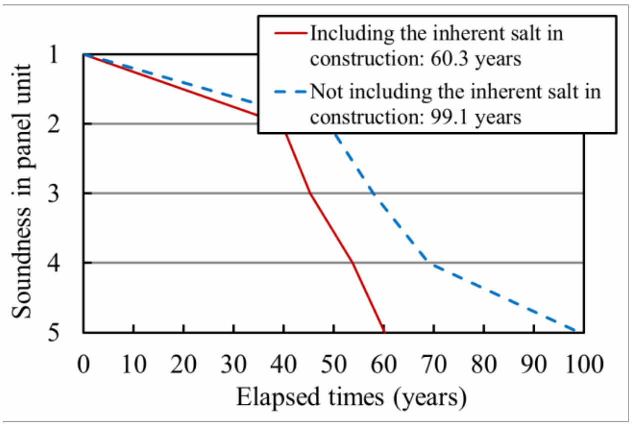

Figure 2. The elapsed times of panel (Deterioration factor: the presence or absence of inherent salt at the time of construction)

Next, it is focused on the application rate of anti-freezing agent. In NEXCO West, the accumulated knowledge in management of the up to now indicates that the deterioration due to salt damage progress is remarkable when the application rate of anti-freezing agent is over 1000t/km. So, the authors analyzed considering whether the application

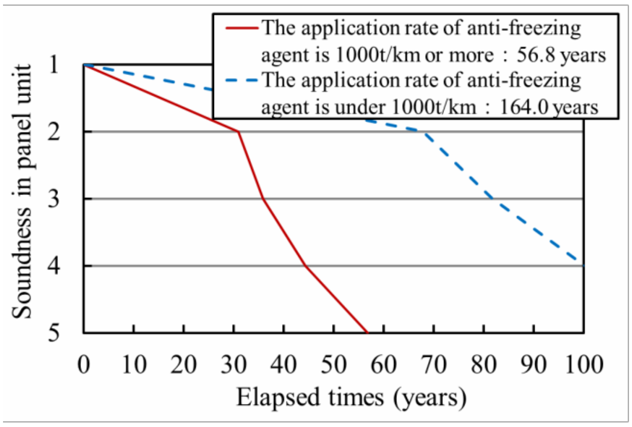

Figure 3. The elapsed times of panel (Deterioration factor: whether or not the cumulative spray volume of antifreeze is 1000 t/km or more)

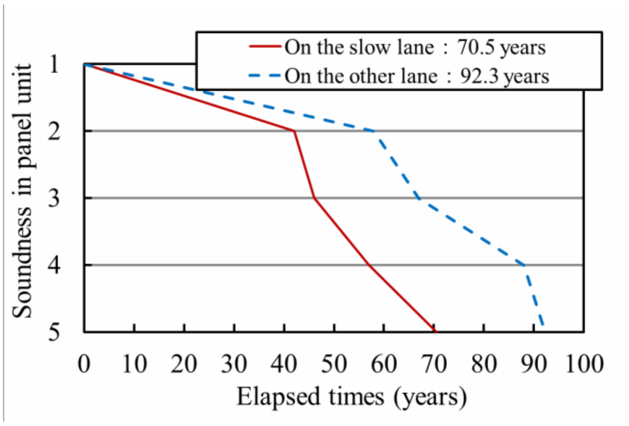

Figure 5. The elapsed times of panel (Deterioration factor: whether or not the large traveling lane of large vehicles)

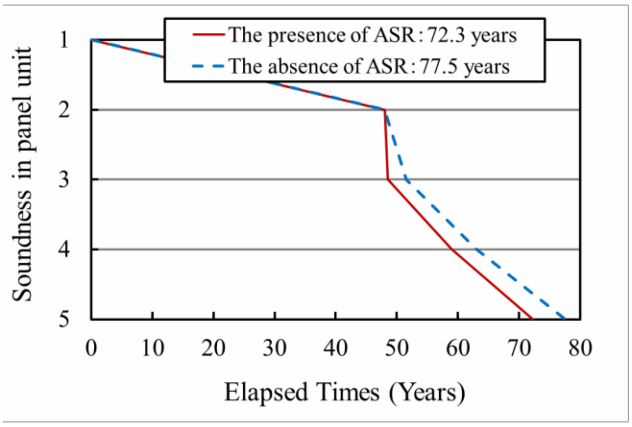

Figure 5. The elapsed times of panel (Deterioration factor: the presence or absence of ASR)

rate of anti-freezing agent is over 1000t/km or not. 5,064 data can be obtained whose application rate of ant-freezing agent is over 1000t/km. Figure 3 shows that the expected lifetime of each panel is 56.8 years when the application rate of anti-freezing agent is over 1000t/km, and the expected lifetime of each panel is 164.0 years when the application rate of anti-freezing agent is under 1000t/km. A difference of expected lifetimes regarding the application rate of ant-freezing agent is 107.2 years; it is so long that only 28 data can be obtained that attains to soundness level 5 in data of that the application rate of anti-freezing agent is under 1000t/km. So, the data bias affect the deterioration speed from soundness level 4 to 5 and panels of that the application rate of anti-freezing agent is under 1000t/km have deteriorate slowly.

The authors focus on the difference of deterioration speed whether the panel is on a slow lane. Recently, the size of traffic volume increases and vehicle advances beyond the assumption of managers and it is serious that the deterioration of RC slabs on slow lane passed large vehicles have progressed. However, it is difficult to prove whether each panel is on slow lane. Therefore, the authors presumed that two vertical panels to a run direction from the slow lane side are on the slow lane and analyzed the deterioration speed. Figure 4 shows that the expected lifetime on the slow lane is 70.5 years and on the other lane is 92.3 years. As this results, owing to increasing the size of traffic volume and advancing vehicle, the deterioration speed of panels on slow lane is rapider than that on other lane. The deterioration factor like it varies by each panel.

The authors refer to the effect of ASR. ASR is the reaction between the specific minerals in the aggregate and alkaline pore solution in the concrete and there are cases that ASR affects the deterioration of the slab. For example, the local expansion in concrete owing to ASR leads to the deterioration such as cracking. In the target data of this study, the

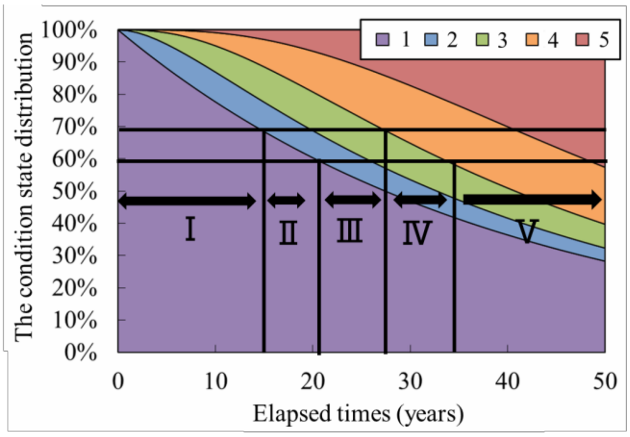

Figure 6. The condition state distribution

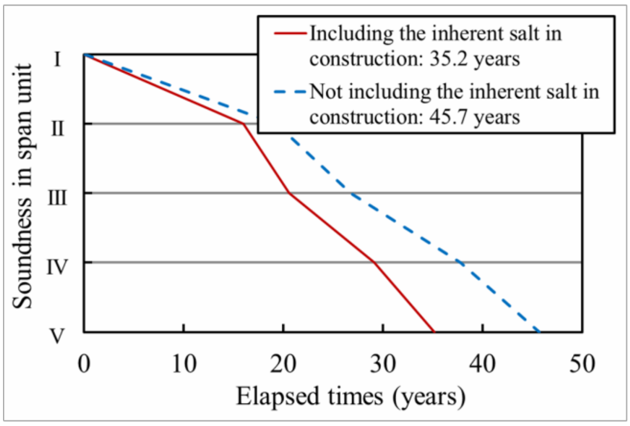

Figure 7. The elapsed times of span
(Deterioration factor: the presence or absence of inherent salt at the time of construction)

generation of ASR are observed at 22 stations among the 290 series. Figure 5 shows the effect of generation of ASR with expected lifetime paths. The expected lifetime is 72.3 years in panels with ASR and 77.5 years in panels without ASR. The effect due to ASR is smaller than those of the inherent salt during construction and the application rate of anti-freezing agent.

4.3 Calculation of the expected life span in span units

Figure 6 shows the condition state distribution that is calculated by equation (3). However, panels falling within the span includes the inherent salt in construction, and the maintenance of all panel units is not assumed to perform. In Figure 6, the vertical axis is a relative proportion of each soundness of panel units, and the horizontal axis is expressed elapsed year. With the condition state distribution in Figure 6 and the condition state determination of span units in Table 2, it is possible to calculate the condition of the span units of an optional elapsed years. For example, when a span composed panels those of less than 30% progress the deterioration over soundness level 2, the condition state of the span unit are determined I, and Figure 4 shows that elapsed time until the condition state of span progresses from I to II is 14.1 years. In other words, 14.1 years is the expected lifetime of the condition state I. Similarly, the expected lifetime of the condition state II is 6.1 years. Figure 7 shows the expected deterioration paths of span units. The vertical axis is the condition state due to span determination, and the horizontal axis is expressed elapsed year. As shown by the red solid line in Figure 7, it takes 35.2 years that the condition state of a span at the time of services commencement with the inherent salt during construction reaches V. From the above, the authors indicated the method to evaluate the expected lifetime corresponded to each the condition state of span with panel unit data. For reference, it also shows the expected lifetime path for the span without the inherent salt at the time of construction by the blue broken line in this figure. It shows that the effect of the inherent salt at the time of construction is 10.5 years.

5. CONCLUSION

In this study, the authors are targeting the record data of inspection units (panel unit data) of RC slabs on an expressway bridge, and analyzes of deterioration factors in detail. As a result, it was appeared that the elements in close contact with the salt damage as the presence or absence of inherent salt in construction and the cumulative application rate of antifreeze have a great effect on deterioration of RC slabs. Furthermore, it was indicated that RC slabs on the driving lane deteriorate rapidly than those on other lane along with the vehicle upsizing. And, it was investigated the influence the presence or absence of ASR affect the deterioration. In addition to these analysis of the deterioration factor in panels units, the authors formulated methodology for determining the expected life in span unit using the Markov chain model to signify the deterioration process in the panel unit. The authors calculated the expected life of the condition state of the span unit using soundness distribution in the panel units.

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