FINITE ELEMENT-LEVEL BRIDGE INSPECTION DATA ANALYSIS AND EXPERIMENTS ON THE DURABILITY OF RC DECKS

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Abstract

A typical deterioration and crack development process for RC decks is well known based on extensive amount of rolling wheel load fatigue tests and crack patterns and densities are considered to account for the remaining durability. However, in reality, the rate of deck deterioration varies widely and sometimes decks seem to suddenly collapse without spreading severe cracks. The present paper conducts a big-data mining to track down the evolution in cracking patterns using bridge inspection data for approximately 20,000 bridges. In addition, rolling wheel load fatigue tests for RC deck specimens are shown where the specimens were sampled out of a decommissioned bridge. The bridge inspection data and experiments have shown that when any crack has developed through the whole depth of deck, the fatigue is considered to have developed further than what surface crack widths and densities look like.

Introduction

Delamination or fatigue in concrete of reinforced concrete (RC) decks is a major concern in bridge maintenance. To test the deck durability in a laboratory, rolling wheel load fatigue tests were developed by Matsui (1984) in Japan and Perdikaris et al. (1993) in the US, respectively. Matsui (1984) has proved that one-directional cracks perpendicular to traffic first develop with a wide space due to a rolling wheel load, followed by the increase in the number of cracks with smaller crack intervals and the evolution into orthogonal cracks. Then concrete fragments partitioned by orthogonal cracks are crumbled with each other and worn out, resulting into a punching failure. Because this is a completely different crack evolution process from the one observed in a

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typical pulsating fatigue load test, where a radial pattern of cracks appears, now rolling wheel loading tests are widely accepted in Japan and regarded as a de facto standard method to examine the durability of decks including RC decks, PC decks, composite decks, steel orthotropic decks, etc. Matsui (1991) also has proved using rolling wheel load tests that the pouring water between cracks accelerates the deterioration process. The reason of the acceleration is often explained as water washes out cement and fine aggregate contents through cracks along with the abrasion between cracks.

However, case histories have indicated that decks not having dense two-directional cracks sometimes seem to abruptly collapse. Figure 1 shows an example, in which a deck having minor two-directional cracks and subtle effloresces collapsed in five months. This kind of deterioration process did not seem to follow the typical crack development pattern, leading a diagnosis of RC deck durability to an unsafe side in bridge inspections.

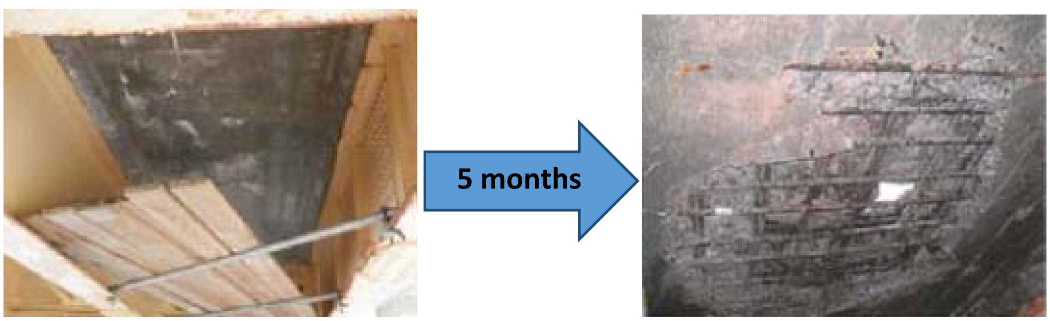


FIGURE 1 An example of the collapse of an RC deck having only minor cracks

Observing crack patterns, widths and densities is an essential and crucial part of RC deck inspections. It is very helpful to elucidate characteristic features that indicate the acceleration of fatigue process in addition to the typical crack evolution process. Accordingly, the present study firstly conducts the data analysis for earlier damage data recordings in bridge inspections. Ministry of Land, Infrastructure, Transport and Tourism (MLIT) started a finite-element level damage data recording at bridge inspections in 2004 for bridges on the national highway routes under the MLIT's jurisdiction. Classified damage types and cracking patterns are required to record for segmental areas of structural members with numeric classification codes along with their extents, 'a' being the least and 'e' being the worst as well as typical photos, sketches, and texts. Secondly, the present study shows a rolling wheel loading test result of deck specimens cut out of an existing bridge. One specimen had some through-thickness crack with efflorescence and the other had no through-thickness crack.

Summary of MLIT's Bridge Inspection Standards

The MLIT bridge inspection standards is applied to any bridge having a span of 2.0 m or longer and owned by MLIT. The inspection frequency is 5 years. Hands-on visual inspection is required. The MLIT bridge inspection standards (MLIT, 2004) is comprised of two parts: maintenance urgency rating and finite-element level damage recording.

Maintenance urgency rating is mandate to diagnose required maintenance actions. Ratings are given for individual structural members. Each structural member in each span is rated for classified damage types with:

- A No repairs needed.
- B No immediate repairs needed.
- C Repair needed
- E1 Emergency action is necessary from the viewpoint of structural safety and stability
- E2 Emergency action is necessary because of other factors.
- M Repairs needed in the course of the regular maintenance work
- S Further detailed investigations needed

Maintenance urgency ratings are given by experienced engineers in a subjective manner in terms of the needs for action by the time of the next inspection. The MLIT's bridge inspection standards describe that maintenance urgency ratings are diagnosed considering the function and importance of the subject structural member, the extent of the subject damage, the expected speed of subject damage evolution, and so forth. In terms of decks, the following supplement is given in the MLIT's bridge inspection standards (MLIT 2004):

- E1 This category can be relevant when notable crack develops and the degradation of the deck rigidity can affect the structural stability of the whole bridge.
- E2 This category can be relevant when crack has developed and reached the state on the verge of punching shear or when the chunks of concrete are likely to fall down and affect the safety of passengers under the bridge.
- S It is suspected that alkali-silica reaction or chloride ingress develops in concrete.
- B or C This category can be assigned, considering the present extent of the subject damage and the expected progression due to surrounding environmental, traffic, and structural conditions.

with supplemental warnings

- When localized severe efflorescence from developed crack is observed together with water seepage, there is a high chance of deck collapse.
- Design loads, the shortage of transverse reinforcement parallel to traffic, and differential deflections between girders, and concrete shrinkage are typical causes of deck crack.

However, maintenance urgency ratings are not a function of numeric criteria for crack width, length, or density and engineers have to judge.

Observed facts such as positions, types and extents of damage appearance are required to record during bridge inspections. Other than conventional fact sheets with photos, texts and sketches, the MLIT bridge inspection standards has required to conduct a finite-element level damage recording since 2004. As shown in Figure 2, elements defined in the MLIT protocols are subdivided segmental portions of individual structural members at individual spans. Figure 3 delineates examples of element categories and element meshing as the units for damage recordings in the MLIT protocol. A line from dot to dot or an area from panel to panel is a finite element. Because the geometry of damage recording units and the data structure are analogous to those of finite element analyses, the present paper refers to bridge inspection 'element' as 'finite element'.

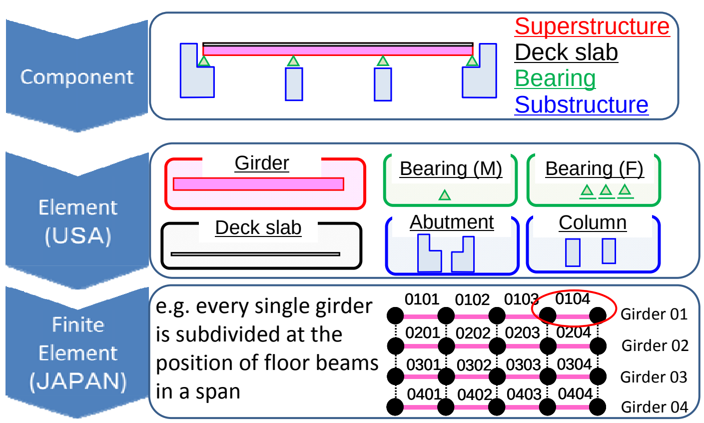


Figure 2. Difference in definition of 'element' in inspection between MLIT (Japan) and the US NBIS

Each finite element possesses the damage data sets for thirteen damage items at maximum and each classified damage is recorded with the relevant extent of damage appearance ranging from 'a' to 'e', where 'a' meaning no damage and 'e' being the worst. A finite element of a steel beam typically has the damage appearance extent data on corrosion-proofing deterioration, corrosion, cracking, and rupture, respectively.

Sometimes only ‘a’ and ‘e’ are defined for particular damage items and sometimes only ‘a’, ‘c’ and ‘e’ or ‘a’, ‘c’, ‘d’ and ‘e’ are defined.

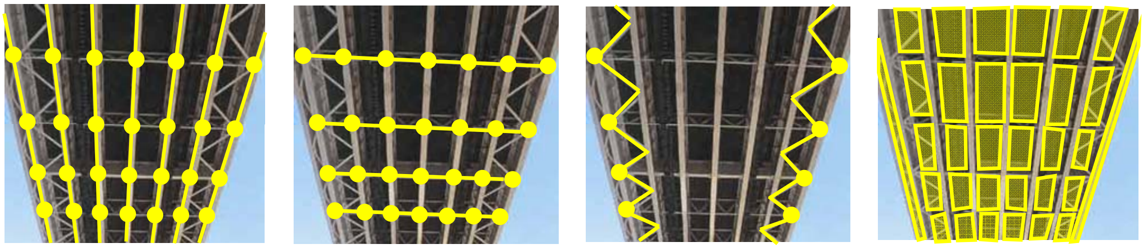


Figure 3. Examples of element categories and finite element meshes in the MLIT’s finite element level bridge inspection

As shown in Figure 3, an RC deck is subdivided into segments, i.e. finite elements, at the position of girders and floor beams. Typical damage items to be recorded are an item of cracks and an item of water seepage and efflorescence. Tables 1 and 2 describe the definitions and typical examples of each extent of damage for deck cracks and water seepage / efflorescence, respectively. Different from maintenance urgency ratings, engineers are required to avoid taking their judgments of expected deterioration speeds or other diagnosis into account in matching with any of extents of damage.

Data Analysis for Damage Recordings in Bridge Inspection

Approximately 20,000 bridges were inspected twice over the last 10 years (from 2004 through 2013). Over 12,000 finite-elements of RC decks were chosen, satisfying with all the following conditions.

- ✓ Finite elements of RC deck were not located at any span end or over bearings on piers.
- ✓ No repair or reinforcement was conducted in the interval between bridge inspections.

Because decks at end spans are likely to be subjected to larger impact loads than those at other areas and those over intermediate supports tend to be subjected to negative bending moments, the present data-mining omit these areas of finite elements.

The change in the extent of damage appearance for deck crack of the same finite element between inspections is tracked down for all chosen finite elements and counted to obtain Markov transition probability matrices. To sum up the transitions, finite elements are classified into two groups as follows:

Group 1: Efflorescence or water seepage was recorded as ‘a’ at the first data recording timings.

Group 2: Efflorescent or water seepage was recorded as ‘b’, ‘c’, ‘d’, and ‘e’ at the first data recording timings.

TABLE 1 Extent of damage appearance for deck crack

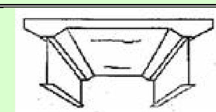
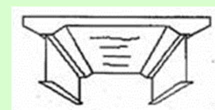
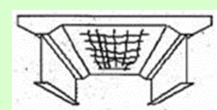
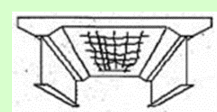
Extent of damage	Numerical criteria for appearance			Examples
	Crack pattern	Crack density	Maximum crack width	
‘a’	One directional crack	Crack spacing is mostly 1.0 m or larger	The maximum crack width is 0.05 mm or narrower (Hair crack)	
‘b’	One directional cracks are prevailed while cracks developing in the bridge axis direction are still minor	Crack spacing is mostly between 1.0 m and 0.5 m	Most cracks have a width narrower than 0.1 mm while some part of cracks have a width of 0.1 mm or wider.	
‘c’	A two-directional crack pattern is developing but it has yet to become like a mesh	Crack spacing is mostly 0.5m and around	Most cracks have a width narrower than 0.2 mm while some part of cracks have a width of 0.2 mm or wider.	
‘d’	A two-directional crack pattern is fully developed	Crack spacing is mostly between 0.5 m and 0.2 m.	Cracks having a width of 0.2 mm are noteworthy and abrasion is visible at some parts of the crack surface	
‘e’	A two-directional crack pattern is fully developed	Crack spacing is mostly shorter than 0.2 m.	Cracks having a width of 0.2 mm are noteworthy and abrasion is well-developed continuously at the crack surface	

TABLE 2 Extents of damage appearance for water seepage and efflorescence

Extent of damage	Appearance
‘a’	No water seepage or efflorescence
‘b’	(NA)
‘c’	Water seepage through any crack or joint is observed but no rust stain or efflorescence is found out.
‘d’	Water seepage and efflorescence through any crack or joint is observed but no rust stain is found out
‘e’	Notable efflorescence is seen, or water seepage involves notable mad-like stain or rust stain

Table 3 shows the counted transitions and Markov transition matrices for Groups 1 and 2, respectively. Because the frequency of bridge inspection is five years, the obtained matrices can be regarded as five-year transition probability. The number of ‘e’-rank finite-elements is few. Probably, decks are repaired before reaching such an extent of damage. However, a notable fact is, in both Groups, several ‘a’- or ‘b’-rank finite elements changed into ‘d’- or ‘e’-rank in five years, meaning RC decks with minor crack sometimes deteriorate in five years. In addition, Table 3 clearly indicates that RC decks with the existence of water seepage or efflorescence tends to have a higher probability to get worse. For example, 25.3% of ‘a’-rank finite elements in Group 1 get worse in five years while the corresponding percentage in Group 2 is 38.5%, 13% higher than in Group 1. For ‘c’-rank finite elements, the percentage to change into ‘d’-rank damage is 3.9% in Group 1 while the corresponding percentage in Group 2 is double, 8%.

TABLE 3 Statistic data and Markov transition matrices for deck crack

(a) Group 1 (when efflorescence or water seepage is not observed)

Extent of damage	# of finite elements		Transition Matrix					Transition Probability Matrix				
			a	b	c	d	e	a	b	c	d	e
a	76,822	5 years	57,422	16,730	2,501	168	1	74.7%	21.8%	3.3%	0.2%	0.0%
b	37,037	⇨	0	34,695	2,205	134	3		93.7%	6.0%	0.4%	0.0%
c	8,515		0	0	8,183	330	2			96.1%	3.9%	0.0%
d	1,244		0	0	0	1,244	0				100.0%	0.0%
e	8		0	0	0	0	8					100.0%

(b) Group 2 (when efflorescence or water seepage is observed)

Extent of damage	# of finite elements		Transition Matrix					Transition Probability Matrix				
			a	b	c	d	e	a	b	c	d	e
a	4,582	5 years	2,818	1,533	216	14	1	61.5%	33.5%	4.7%	0.3%	0.0%
b	9,209	⇨	0	8,650	511	47	1		93.9%	5.5%	0.5%	0.0%
c	1,980		0	0	1,821	158	1			92.0%	8.0%	0.1%
d	270		0	0	0	267	3				98.9%	1.1%
e	23		0	0	0	0	23					100.0%

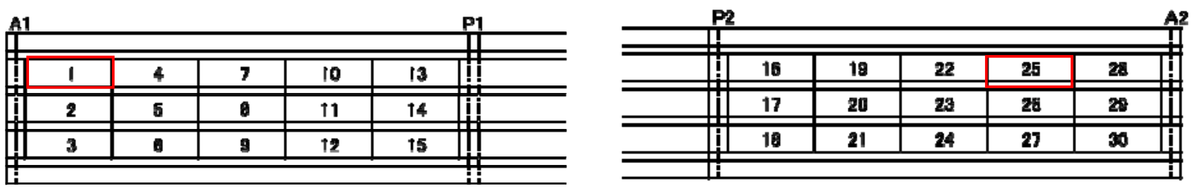
Durability Tests for Used RC Decks

To back up the bridge inspection data analysis, the present study has also conducted an experimental study using a rolling wheel loading machine. To minimize scale effects in laboratory tests on the deterioration process in concrete, the present study employed two RC deck specimens that were cut out of a decommissioned bridge. The decommissioned bridge was shown in Figure 4. It was put in service in 1972 and demolished in 2009 at 39 years old. The design was complied with the 1964 Japanese Specifications for Highway Bridges. All spans had 24.7 m in length. The skew angle was 80 degree. A four I-beam girder system with RC deck was used and the spacing of the girders was 2.0 m equally. As shown in Figure 4, the RC decks in Spans #1 and #3 were dissolved into 30 pieces on site and the areas of no. 1 and no. 25 marked with red squares were chosen as the specimens. The following conditions were considered when sampling the specimens:

1. One sample has through-thickness cracks while the other does not have.
2. Except for the existence or non-existence of through-thickness crack, crack distribution densities, patterns, and widths seem equivalent as much as possible.

3. The samples were cut out of the same lane because loading histories were considered similar to each other, where the positions of presumed axel loading and the sampled specimens are also drawn in Figure 4.

The deck thickness was 170 mm and it did not have waterproof work. No repair was conducted in the past for the RC deck. The reinforcement arrangement of the deck is also summarized in Figure 4.



Plan view

Deck span = 2.0 m, Deck thickness = 170 mm		
Main reinforcement perpendicular to traffic	Top	D16@250
	Bottom	D16@125
Distribution reinforcement parallel to traffic	Top	D16@300
	Bottom	D16@150

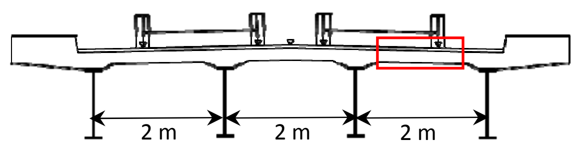


Figure 4   RC deck specimens cut out of the decommissioned bridge (Specimens no. 1 and no. 25 were finally employed.)

Crack widths and distances in both specimens were measured and compared in Table 4, with photos of the bottom surface appearance, for both specimens. Except for the fact that subtle efflorescence locally appeared as shown in the specimen no. 1, crack patterns, widths and densities were found out similar to each other when comparing the specimens. After removing asphalt pavement, the water permeability was tested, proving that the specimen no. 1 had through-thickness cracks and the specimen no. 25 had none of them. Concrete and reinforcement were sampled from both specimens and tested, as summarized in Table 5. Both specimens have similar material properties. The sampled specimen dimensions were 1.4 m wide perpendicular to traffic and 3.85 m long parallel to traffic and these widths and lengths were too short to place the specimens on the rolling wheel loading machine. Accordingly, concrete and reinforcement was added to the perimeters of the specimens, and the dimensions of the specimens ended up to be 2.0 m wide perpendicular to traffic and 4.5 m long parallel to traffic.

TABLE 4 Observed crack widths and spacing in the sampled specimens

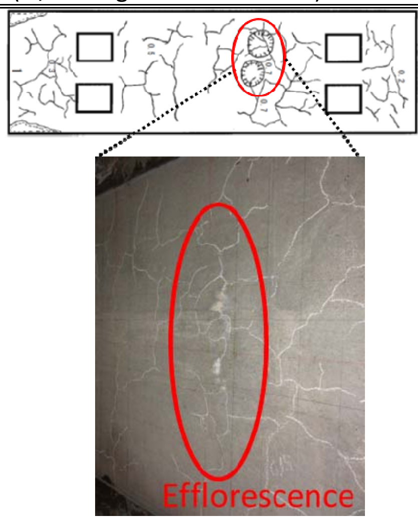
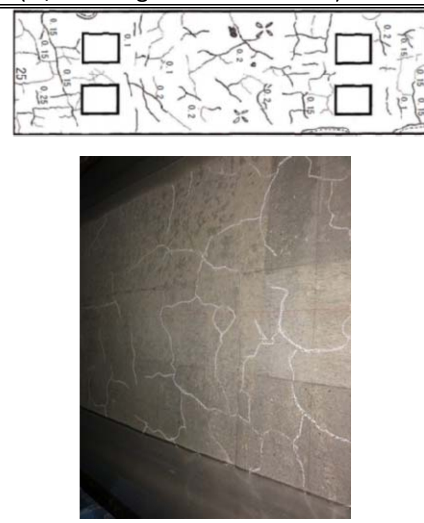
	Specimen no. 1 (w/ through-thickness crack)	Specimen no. 25 (w/o through-thickness crack).
Bottom surface appearance		
Crack width	0.10 mm to 0.25 mm	0.10 to 0.20 mm
Crack spacing	0.2 m to 0.3 m	0.2 m to 0.3 m

TABLE 5 Material test results

		Specimen no. 1 (w/ through-thickness crack)	Specimen no. 25 (w/o through-thickness crack)
Concrete	Strength	33.1 N/mm^2	34.1 N/mm^2
	Young's modulus	27.3 kN/mm^2	22.3 kN/mm^2
Reinforcement	Yield strength	372 N/mm^2	387 N/mm^2
	Young's modulus	213 kN/mm^2	202 kN/mm^2

A rolling wheel loading machine owned by the Public Works Research Institute (PWRI), Tsukuba, Japan, shown in Figure 5 was used. The wheel was made of steel and its width and diameter were 0.3 m and 7 m, respectively. The machine has a capacity of rolling back and force at a maximum frequency of 2,000 repeated cycles per hour while applying a vertical load in the range up to 490 kN on the specimen that can be programmed to change along with the number of repeated wheel movement cycles.

Figure 5 also shows the boundary conditions of the specimen. Both the longitudinal ends parallel to traffic were free to rotate and slide, being supported by metal rollers. Both transverse ends perpendicular to traffic were supported elastically by steel H-beams. To avoid the separation of the transverse edges from the supports during loading, the specimens were fixed to the supports using rods while the rotation was kept free. The supporting H-beams were designed so that the deformation of RC deck specimens can model the behavior of the same RC deck with infinite length in the bridge longitudinal direction. An elastic finite element analysis was used to compare the behavior of the specimens to that of the assumed specimen with the infinite length in the bridge longitudinal direction.

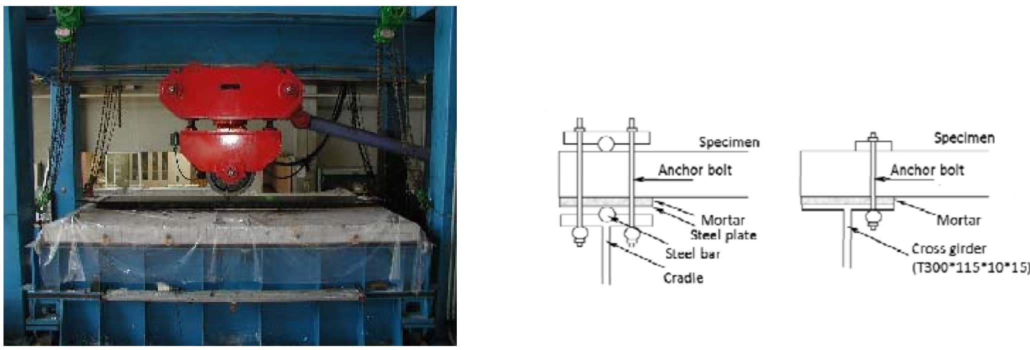
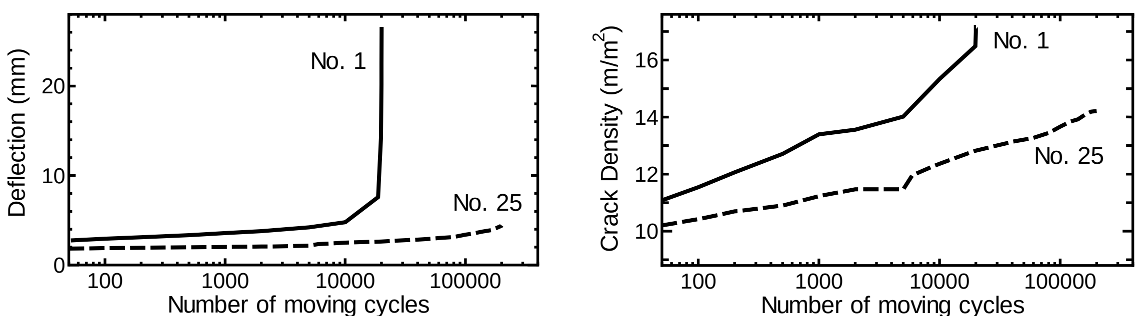


FIGURE 5 Rolling wheel loading test machine (Public Works Research Institute, Tsukuba, Japan) and test set-ups of boundary condition

The present test employs one of the de facto loading protocols in Japan (Matsui 1985, Nakatani et al. 2002). The rolling wheel moved back and force ±1.5 m from the center of the specimen in the traffic direction along the center line of the specimen. The axel load was set to be 157 kN, while the bridge design axel load is 100 kN. Based on previous nation-wide WIM measurements on different national highway routes covering a wide range of ADTTs (e.g. Tamakoshi et al. 2006), an axel load of 157 kN is considered equivalent to the record maximum. To avoid an unrealistic stress concentration on the specimen, rectangular steel blocks of 300 mm wide, 120 mm long, and 55mm deep were laid out along the center line on the specimen, which models a wheel contact area at a scale of 60% to the design wheel contract area in the bridge design specifications, that is 500 mm wide and 200 mm long (Japan Road Association, 2012). The top surface of the specimens underneath the steel blocks were covered with epoxy resin to make the top surface smooth and flat, with a due caution not to penetrate it into crack using polyethylene sheets, where the maximum resin depth was ended up to vary from approximately 20 mm to 2 mm. Although earlier studies have shown that spraying water on the deck surface during a test accelerates the deterioration, the present experiment was run in a dry condition.

Test Results

At the initial static loading at the center of the specimens, the specimens #1 (with through-thickness crack initially) and #25 (with no through-thickness crack initially) deflected 2.76 mm and 1.83 mm, respectively. The rigidity of the specimen #1 was smaller than that of the specimen no. 25, while the difference in the material test results is negligible as shown in Table 5. Figure 6 compares the relationships between the number of repeated wheel moving cycles and the deflection at the center of the specimen and those between the number of repeated wheel moving cycles and the crack density, where crack density is defined as the ratio of the total crack length to the area of specimen. In the measurement of the crack density, cracks with a width of 0.05 mm or wider are counted. The specimen no. 1 (with through-thickness crack initially) underwent the sudden increase in the deflection and crack density at a repeated wheel moving cycle of 20,000, resulting in the punching shear failure at the 20,050 repeated wheel moving cycle. However, both deflection and crack density in the specimen no. 25 (with no through-thickness crack initially) did not show a sudden increase even at a repeated wheel moving cycle of 200,000, that is one order higher than the ultimate wheel moving cycle in the specimen no. 1. These results show that even a small sign of through-thickness crack should mean the deck deterioration has developed more than what crack spacing and density look like.

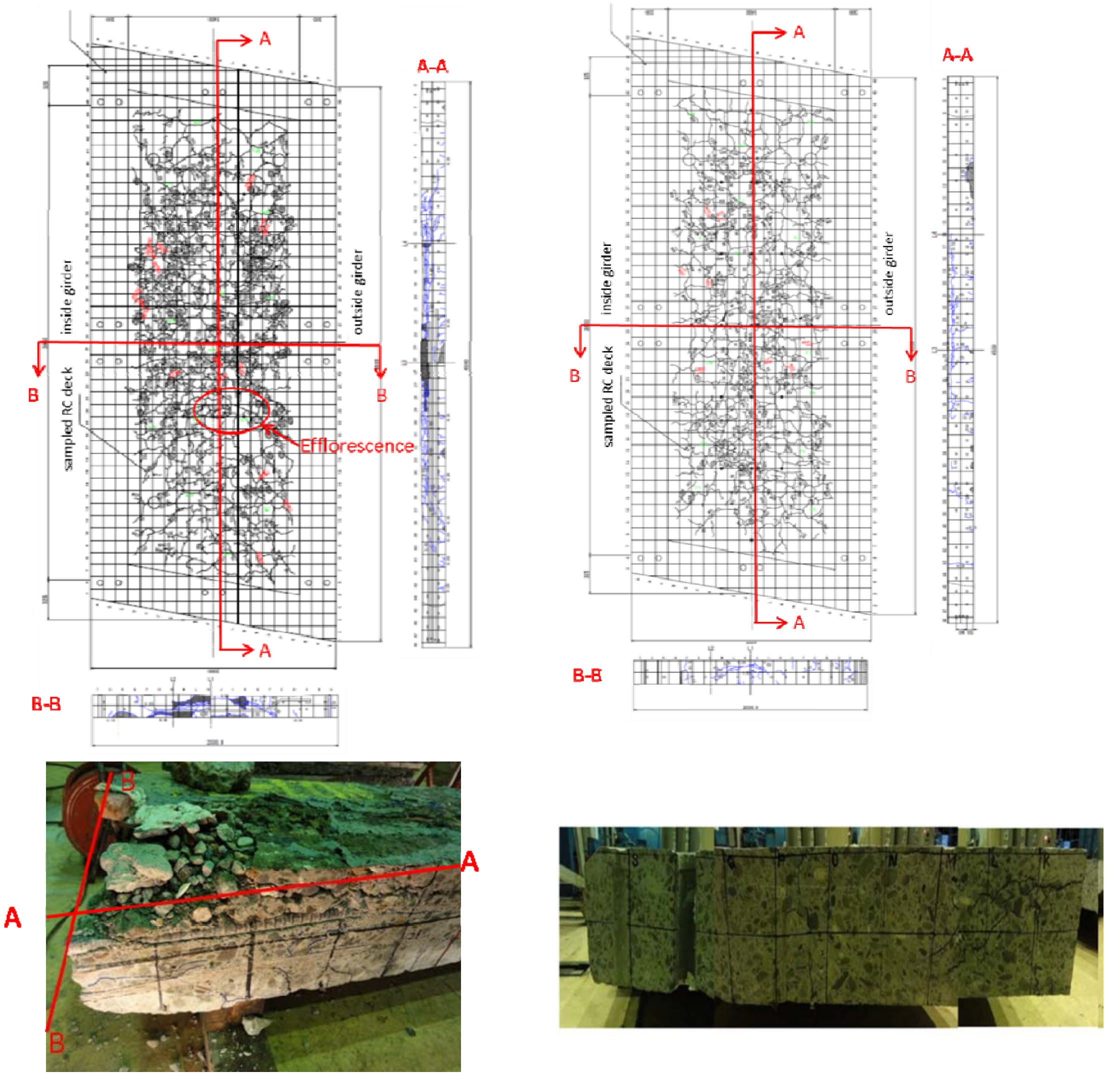


Relationships between the span-center deflection and the number of moving cycles

Relationships between the crack density and the number of moving cycles

FIGURE 6 Evolution in deflection and crack density with increasing the number of moving cycles

Figure 7 compares the states of both specimens after the tests. The specimens were cut to observe crack patterns at the cross-sections along the center lines perpendicular and parallel to traffic. The concrete in the specimen no. 1 (with through-thickness crack initially) was delaminated along the top reinforcement. The concrete of the upper surface of the specimen became like gravels, which is typically seen in reality in deteriorated RC decks. The specimen no. 25 also had horizontal cracks along the top reinforcement. However, the crack width is narrow and no major progress in deterioration was observed.



Specimen no. 1
(w/ through-thickness crack initially)

Specimen no. 25
(w/o through-thickness crack initially)

FIGURE 7 Final states of the specimens

Concluding Remarks

The present paper first tackled the data analysis of finite element-level damage recording in bridge inspections in MLIT to see the variation in deterioration process of RC decks. The damage data have indicated that finite elements of RC deck with the existence of efflorescence or water seepage from crack have a higher probability to worsen in five years. The data also indicate that even RC decks with minor crack sometimes will deteriorate and have two-directional crack in five years. A wheel running loading test has been conducted in a dry condition using RC deck samples. Two samples were cut out of the same lane of an existed 37 years old bridge. Crack densities and widths seemed undiscernible between both specimens. The test results have proved that the existence of through-thickness crack with efflorescence in concrete means the deterioration has evolved than what the crack pattern of width and density look like, even though the previous loading histories are similar and deck water proof condition is the same. This agrees with the statistical analysis result for bridge inspection data.

These results are referred to when the MLIT Bridge Inspection Standards was revised in July 2014. Table 6 shows the new RC deck damage recording protocol. NILIM will continue to keep tracking down the finite element level damage recording data to find out the scientific facts for R&D in the field of design, construction quality, inspection, and maintenance.

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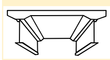
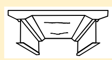
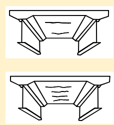
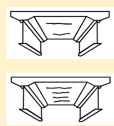
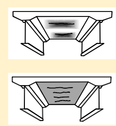
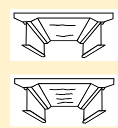
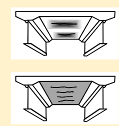
TABLE 6 Revised definition of the extents of damage for deck crack

(a) #1 One-directional crack

Extent of damage	'a'	'b'	'c'	'd'		'e'	
Water seepage or efflo-Rescence	Absent	Absent	Absent	Absent	Present	Absent	Present
Crack density	None	Most crack distances are 1.0 m or larger.	Any crack distance applicable to this category	Any crack distance applicable to this category		Any crack distance applicable to this category	
Maximum crack width	None	0.05 mm or narrower (Hair crack)	Still narrower than 0.1 mm in most cracks.	Still narrower than 0.2 mm in most cracks		Cracks having a width of 0.2 mm are noteworthy and abrasion is developed partly at the crack surface	
Examples							

(b) #2 Two-directional crack

Extent of damage	'a'	'b'	'c'	'd'		'e'	
Water seepage or efflo-Rescence	NA	NA	Absent	Absent	Present	Absent	Present
Crack density	NA	NA	Blocks with dimensions of 0.5 m x 0.5 m or larger	Blocks with dimensions between 0.5 m x 0.5 m to 0.2 m x 0.2 m	Any crack distance applicable to this category	Blocks with dimensions of 0.2 m x 0.2 m or smaller	Any crack distance applicable to this category
Maximum crack width	NA	NA	Still narrower than 0.1 mm in most cracks.	Maximum crack widths are still narrower than 0.2 mm in most cracks		Cracks having a width of 0.2 mm are noteworthy and abrasion is developed partly at the crack surface	
Examples	NA	NA