FATIGUE DURABILITY OF A REINFORCED CONCRETE
DECK SLAB IN A COLD SNOWY REGION

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Abstract

Repeating large Wheel loading from large vehicles are known to be the major cause of the deterioration and fatigue failure of reinforced concrete (RC) deck slabs on road bridges. Added to this, the intrusion of rainwater into cracks significantly reduces the fatigue durability of deck slabs. Other environmental conditions also accelerate the deterioration. In Hokkaido, the extreme cold causes freezing damage, and the spreading of deicing agents causes salt damage. To manage the repair of deck slabs in a cold region, it is necessary to determine how their states of deterioration relate to their lifespans. To study the fatigue durability of deck slabs, we performed fatigue tests using a wheel tracking test machine. Test specimens showing typical deterioration is typical of cold regions were cut from the deck slab of a bridge that was in service in Hokkaido.

Introduction

Deterioration of the reinforced concrete (RC) deck slabs of road bridges is attributed largely to fatigue from repeated wheel loadings, particularly of heavy vehicles. Penetration of rainwater into cracks in the deck slab is thought to accelerate the reduction of fatigue durability. In Hokkaido, deterioration is further accelerated by frost damage and by the spreading of deicing agents, which causes salt damage to concrete structures. In cold regions, it is necessary to quantitatively evaluate the relationship between the level of damage and the remaining lifespan of RC deck slabs by considering the deterioration process.

To study the fatigue durability of RC deck slabs in such regions, fatigue tests were performed with a wheel-loading test machine on test specimens cut from the deck slab of a bridge in Hokkaido.

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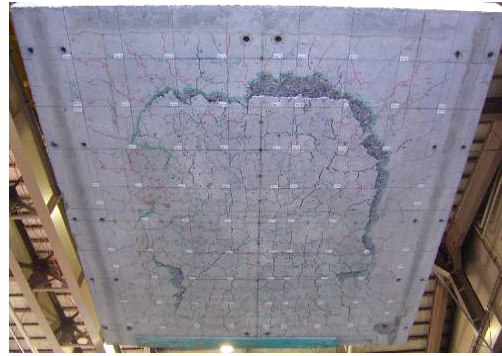3 Researcher, Structures Research Team, CERI, PWRI
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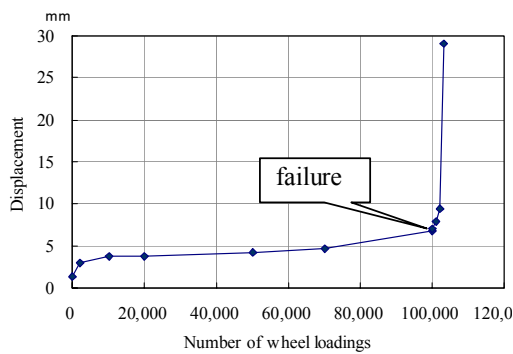5 Team Leader, Structures Research Team, CERI, PWRI
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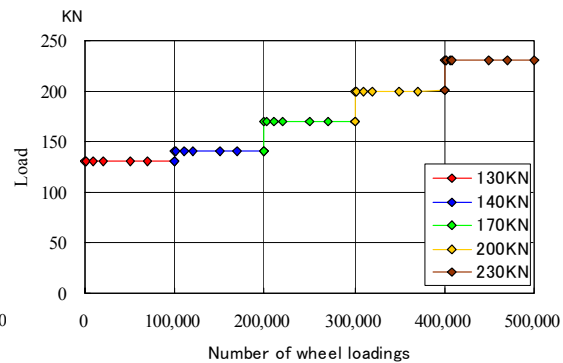
Photo 1   Wheel loading test machine

Photo 2   Punching shear failure at the lower surface of the deck slab

Figure 1   Wheel loadings vs. displacement

Figure 2   Loading pattern

Outline of the test
a) Test method

      It show in the Photo 1, the wheel loading test machine is capable of imposing vertical loads of up to 300 KN. The reciprocating movements of the wheel reproduce punching shear failure (Photo 2), a failure mode that is typical of RC deck slabs. This paper defines failure of an RC deck slab as the point where the curve of the number of wheel loadings vs. displacement turns up sharply (Figure 1).

      The wheel loading test was conducted in the incremental loading pattern shown in Figure 2, which is recommended by the Ministry of Land, Infrastructure and Transport. From the degree of damage to the bridge, early failure of the test specimen was expected, and the initial load was decided to be a relatively light 130 KN. The test specimens were simply supported at both ends and were elastically supported at both sides. To examine changes in deflection, deflection was measured at the numbers of wheel loadings marked with diamond marks in Figure 2, with static wheel loading and without loading.
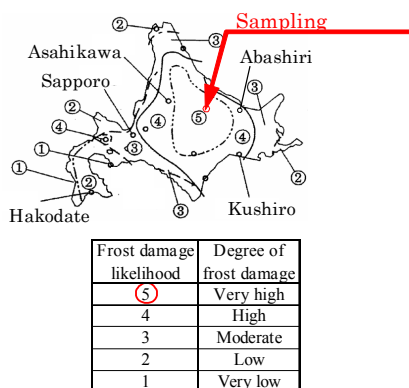
Figure 3 shows frost damage distribution with map and a table:

Frost damage likelihood	Degree of frost damage
⑤	Very high
4	High
3	Moderate
2	Low
1	Very low

Figure 3　Frost damage distribution

Table 1　Test piece details

Dimensions (cm)		230*300*18
Quality of rebar		SR235
Main reinforcement (mm)	Upper	φ16@200
	Lower	φ16@100
Distribution bar (mm)	Upper	φ13@200
	Lower	φ13@200
Compressive strength of concrete (N/mm^2)		A 45.5
		B 41.0
		C 49.8
		Benchmark 40.9

(a)　Side view

(b)　Top view

(c)　Cross section
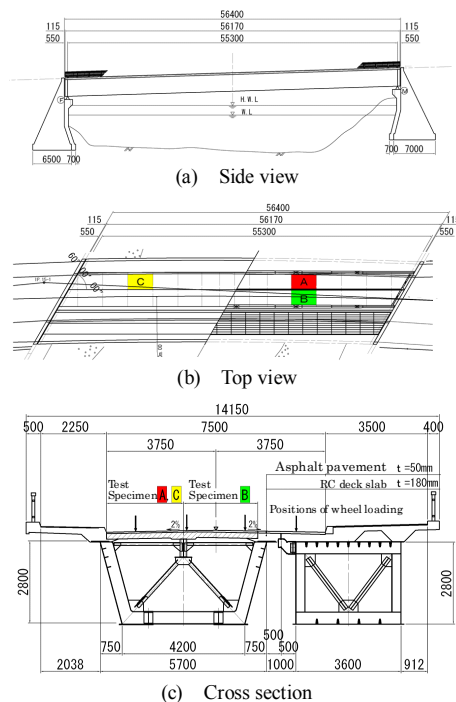
Figure 4　Sampling locations of deck slab test specimen

(a) Upper surface of deck slab　(b) Cross section of deck slab　(c) Lower surface of deck slab

Photo 3　Deterioration of test pieces

Test specimen A	Test specimen B	Test specimen C

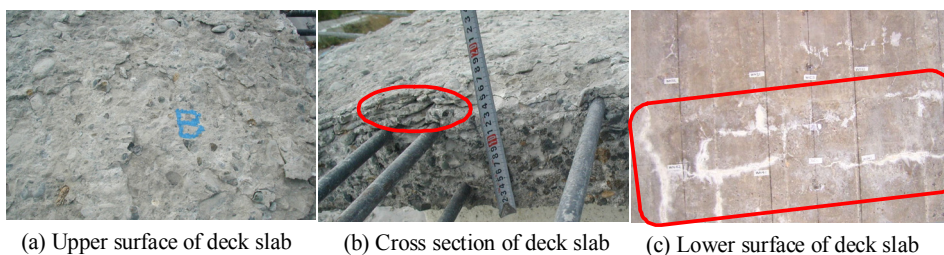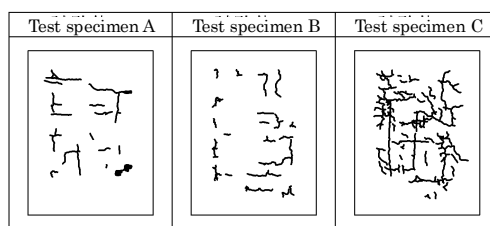**Figure 5**　Cracks at the lower surface of deck slabs before the wheel loading test

b) Test specimens

　　The test specimens were taken from a box-girder bridge that had been in service for 42 years on Route 39, which connects the cities of Asahikawa and Abashiri, Hokkaido. According to the frost damage risk distribution chart[1] shown in Figure 3, this bridge is in a region with the highest risk (Level 5).　Four test specimens were used in the fatigue test,

three of them (A, B and C in Figure 4) sampled by cutting specimens from the bridge deck, and a fourth fabricated as a deterioration-free benchmark test specimen for comparison.

The bridge was designed in accordance with the Specification for Steel Highway Bridges (1956), and the test specimens are described in Table 1. The degrees of deterioration of the deck slabs from which the test specimens were cut are shown in Photo 3, and sketches of cracks in the lower surface of the slabs are shown in Figure 5. Wide areas of the slab upper surface show scaling from frost damage. The cross sections show delamination of the upper concrete cover. In the most severe case, the rebars were exposed. At the lower surface of the deck slab, the crack widths were about 0.1 mm, and from these cracks, a considerable amount of free lime release was observed. Visual inspection showed deterioration as follows:

1) Test specimen A

Scaling was observed over the entire upper surface, and delamination had caused the loss of about 25 mm of the concrete cover. The crack density at the lower surface was 1.9 m/m^2, and some of the edges there were observed to have broken off.

2) Test specimen B

This test specimen was adjacent to test specimen A; the degree of deterioration was similar to that of test specimen A.
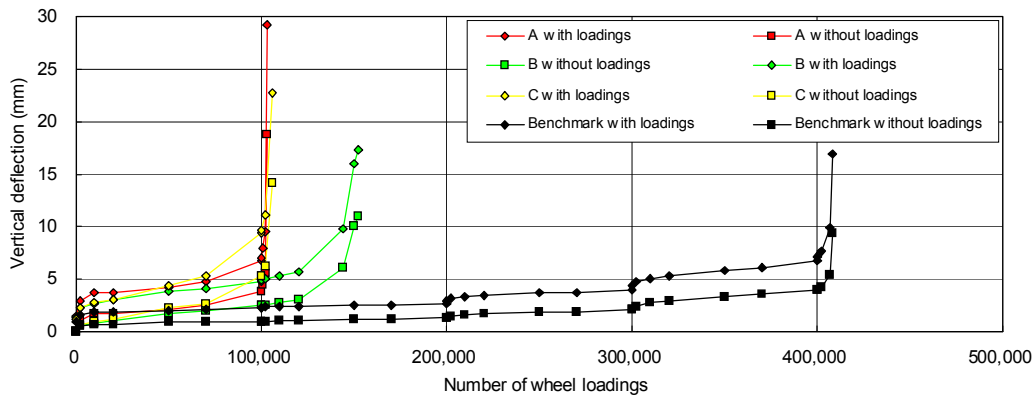
3) Test specimen C

Scaling was observed on about 20% of the upper surface, and delamination had caused the loss of about 20 mm of the concrete cover. The crack density at the lower surface was 6.0 m/m^2.

The compressive strengths of concrete listed in Table 1 were obtained through compression tests performed on core samples taken from portions that were relatively intact and that excluded the upper cover concrete. Attempts were made to measure the strengths of concrete at the upper surface with a Schmidt hammer. However, the strength was immeasurable on all three test specimens. The strength of the concrete at the upper surface was estimated to be less than 10 N/mm^2.

c) Material testing of test specimens

Material tests on core samples taken from the bridge proved no alkali-aggregate reaction in the concrete. A neutralization test found that chloride ion intrusion was less than 2 cm at the lower surface of the deck slab. The test on chloride content found a chloride ion concentration at the upper surface of the deck slab (at the depth of the rebars) of 0.1 kg/m^3, compared to the corrosion threshold of 1.2 kg/m^3 (i.e., the concentration at which corrosion starts). Although neutralization and chloride intrusion were observed, they were not at levels that could reduce the durability of the deck slab.

Figure 6 Wheel loadings (before conversion) vs. deflection

Table 2 Numbers of loadings at failure

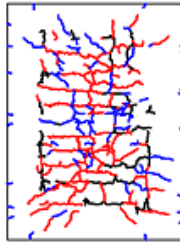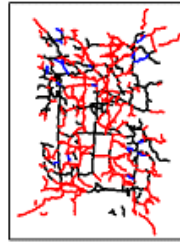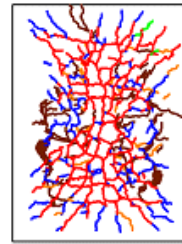| Test specimen	Converted loadings (kN)	Converted number of loadings
A	150	210000
B	150	460000
C	150	220000
Benchmark	150	76760000

This shows that frost damage is the only major factor in environmental deterioration. Therefore, it was assumed that slab deterioration was accelerated by contact with water containing chlorides and by the freeze-thaw cycles that are typical of cold regions.

Test results
a) Number of wheel loadings at failure

The relationship between the number of wheel loadings and the deflection at the center of the test specimens is shown in Figure 6 for total deflection under load and for residual deflection without load. At failure, the critical deflection can be read as 5 to 10 mm for total deflection and 3 to 5 mm for residual deflection. Then, the number of wheel loadings to the point of failure is obtained, as shown in Table 2, by converting the incremental loadings to a constant load of 150 KN and converting the width of the test wheels to that of standard vehicle wheel. From the number of wheel loadings, it was found that the number of wheel loadings at failure for the three frost-damaged test specimens is 1/167th to 1/366th less than that for the benchmark specimen. This verifies the importance of installing waterproofing layers on deck slabs.

Test specimen A failed at about half the number of wheel loadings as for test specimen B, even though the two test specimens showed similar degrees of deterioration. This difference is attributed to the relative positions of the test specimens: Test specimen B was slightly farther from the position of vehicle wheel loadings than test specimen A. It was thought that fatigue from wheel loads had been accumulated in test specimen A.

Test specimen	A	B	C	D
Crack density	11.15 (m/m^2)	10.55 (m/m^2)	13.84 (m/m^2)	14.82(m/m^2)
The lower surface of deck slabs				

Figure 7 Cracks at failure of the lower surface of deck slabs
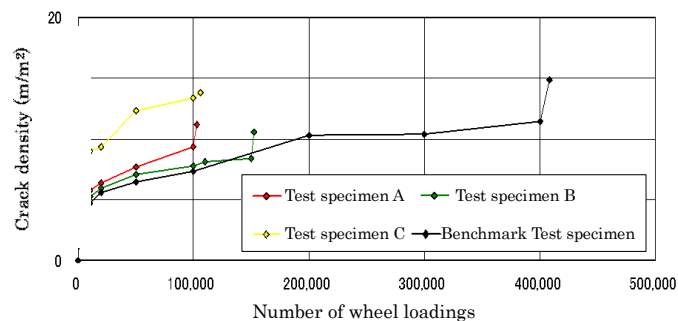
**Figure 8** Wheel loadings (before conversion) vs. crack density

b) Crack density at failure

Figure 7 shows cracking at the lower surface of the deck slab at failure. Figure 8 shows the relationship between the number of wheel loadings (before conversion) and the crack density. Similar to deflection, crack density increases proportionally to increases in the number of loadings up to failure; crack density was about 10 m/m^2 at failure for test specimens A and B. This is consistent with the threshold crack density previously reported by the authors[2] (i.e., the density beyond which the deck slab is no longer sound). On the other hand, test specimen C, which had a high crack density of 6.0 m/m^2 before the wheel loading test, and the benchmark test specimen, which had deteriorated only from fatigue, show relatively high crack densities of 14 to 15 m/m^2.

The elastic moduli (Ec) of test specimens A and B, obtained from the static elasticity test, were about 2.6 x104 N/mm^2 for test specimens A and B, versus maximum values of about 3.1 x104 N/mm^2 for test specimen C and the benchmark test specimen. This difference is thought to have contributed to the differences in crack densities.

Fatigue durability of concrete deck slabs in cold regions

The curve of stress vs. number of wheel loadings (S-N curve) in Figure 9 is expressed with the ratio of equivalent load (P) to shear capacity (Psx) on the vertical axis and the number of wheel loadings on the horizontal axis. The chart plots the numbers of
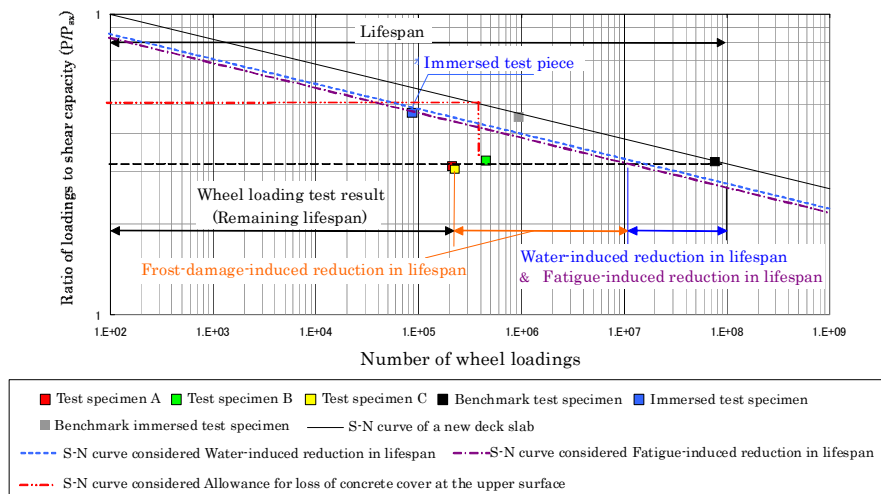
Figure 9 S-N curve
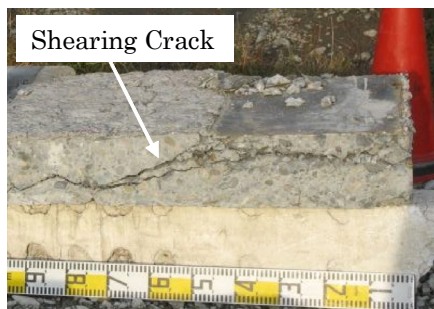
Photo 4 Cut section of the bridge deck slab
(transverse direction)

Photo 5 Cut section of the bridge deck slab
(directly below the wheel travel position)

wheel loadings at failure for the three test specimens sampled from the bridge and the one benchmark test specimen, with loadings converted to 150 KN. In 2006, test specimens were immersed in water to determine the effect on fatigue durability. Figure 9 also plots the fatigue durability of the immersed test specimens. Since the test specimens in this previous test had a slab thickness of 17 cm and a compressive strength of about 28 N/mm^2, their shear capacities were less that those of the test specimens in the current test.

The benchmark test specimen and the benchmark immersed test specimen were intact at the beginning of the test and were deteriorated by wheel loading. Figure 9 shows S-N curves for the non-immersed test specimen and for the immersed test specimens. These curves indicate the lifespan, in terms of the number of wheel loadings at failure.

From data on the cumulative volume of heavy vehicles on this bridge (the Road Traffic Census (1999)) and a study on the frequency distribution of axle loads[3], the number of wheel loadings during the service period was estimated to be 640,000. A curve that shows deterioration from fatigue is plotted parallel to the S-N curve in Figure 9.

The number of wheel loadings at failure for each of the three test specimens is

much less than the number of wheel loadings at failure for a slab deteriorated by water and fatigue. The difference between the number of wheel loadings at failure for each of the three test specimens and the number of wheel loadings at failure for a slab deteriorated by water and fatigue is regarded as the frost-damage-induced reduction in lifespan. The number of wheel loadings at failure for the immersed test specimens was 1/11th that for the benchmark test specimen. For frost-damaged deck slabs in cold regions, the number of wheel loadings at failure was 1/15th to 1/33rd that for the benchmark test specimen.

After the tests, the test specimens from the bridge were cut to examine the deterioration. Photo 4 shows a transverse section of the deck slab, and Photo 5 shows a longitudinal section of the deck slab at the line of wheel travel. As observed in Photo 4, the failure mode of the frost-damaged deck slab was punching shear failure. In Photo 5, the concrete has crumbled in the surface layer and in the layer of the upper reinforcements, and it is assumed that the shear resistance of this portion of concrete has been reduced.

From the above, the shear capacity (Psx) that ignores the 4 cm of concrete cover was calculated, and it is plotted in Figure 9 as the red dashed line. The number of wheel loadings at failure (i.e., the lifespan) of a deck slab without concrete cover is roughly the same as that of the test specimens from the bridge. This can serve as a reference in estimating the remaining lifespan of frost-damaged concrete deck slabs in cold regions.

Conclusion

The findings are summarized here.
The number of wheel loadings at failure for frost-damaged test specimens was 1/167th to 1/366th that for a deterioration-free benchmark test specimen.
The number of wheel loadings at failure for frost-damaged, water-immersed test specimens was 1/15th to 1/33rd that for a frost-damage-free, water-immersed test specimen.
The reduced durability of concrete deck slabs in cold regions is attributed to the reduction in shear capacity caused by the separation of aggregate and mortar in the concrete at the top of the deck slab. The number of wheel loadings at failure for a deck slab without concrete cover was roughly the same as those for the test specimens from the bridge.

References

1) Hasegawa, T., et al.: "Durability of concrete structures: Frost damage," Gihodo Shuppan Co., Ltd., 1988.
2) Maeda, Y., Matsui, S.: "A method for identifying deterioration in reinforced-concrete bridge deck slabs," Proceedings of the Japan Society of Civil Engineers, No. 374, pp. 419-426, 1986.
3) Mitamura, H., Adachi, Y., Ishikawa, H.: "Remaining lifepan of bridge deck slabs estimated from wheel axle loads," Monthly Report of the Civil Engineering Research Institute for Cold Region, No. 637, pp. 2-16, 2006.