FATIGUE DAMAGE ASSESSMENT FOR STEEL-CONCRETE COMPOSITE DECK

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***ABSTRACT*:** This paper shows the damage process of steel-concrete composite deck subjected to high-cycle moving load by using experimental study and numerical analysis. The analysis is based on fatigue constitutive models for concrete as well as proposed interface element between steel and concrete. Both experiment and analysis proved that the failure mode of composite deck is strongly affected by the surface condition of the ribs. Especially the cracks on the surface concrete caused by the bond loss are considered to be a damage indicator of composite deck. In order to find this indicator, periodical inspection of pavement and nondestructive test are recommended.

KEYWORDS: steel-concrete composite deck, fatigue, mid-span deflection

1. INTRODUCTION

As bridge decks suffer from severe environmental condition, such as repetition of drying-wetting, chloride attack mainly by deicing chemicals and high-cycle traffic load, durability of deck sometimes becomes major issue of bridge management system rather than that of the main structure. Investigation of decks is required from two points of view. One is to know present damage of decks. Another is to estimate their future performances. This paper focuses on the high-cycle fatigue problem of bridge deck.

As for fatigue problems on steel decks, a lot of knowledge has been accumulated in the field of steel structure engineering. As for fatigue problems on concrete decks, reinforced concrete decks have been investigated both experimentally and analytically. Different groups of researchers installed a wheel-type moving load testing machine. They conducted various experiments since 1980 (Matsui 1987; Pedikaris and Beim 1989). Based upon the results of these experimental studies, they could come up to the fatigue damage mechanism under the traffic load. Moreover, numerical analyses are tackling fatigue problem of concrete. Peerapong and Matsumoto analyzed concrete fatigue regarding distributed cracks and the bridging stress degradation characteristics by using finite element method (2006). Maekawa *et al*. have developed an original nonlinear finite element analysis framework “COM3” that fully traces mechanical damage and plasticity under high cycle repetition of loads in use of logarithmic accelerated time integration. They also have verified applicability of this framework (2006a, 2006b). In addition, Minagawa *et al*. showed a practical management model of reinforced concrete deck that makes versatile inference based on the knowledge shared and obtained in the real field (2001).

In contrast, the number of investigation of steel-concrete composite decks is small as compared to above mentions. Steel-concrete composite decks mainly consist of bottom steel plate, concrete deck and shear connector that transfer stress from one to another. Since bottom steel plate hide visible damage sign from concrete, such as crack spacing, length and width, it is hard for engineers to obtain damage information in practice. Meanwhile, engineers proposed various kinds of shear connectors, such as studs and ribs. This makes the fatigue analysis of composite deck complicated, too. Hawkins and Mitchell pointed out that failure mode of composite structure is greatly influenced by the mechanical property of shear connector (1984). In order to know damage state of composite deck at each step, the authors attempt to analyze fatigue problem of steel-concrete composite decks by using an enhanced model of “COM3” including the interface friction model proposed by Maekawa *et al.* (2008).

First, three specimens with different rib conditions were prepared to consider the effects of interface friction. Second, the authors simulated the experimental results by using finite element analysis package, COM3. Analysis provided possible explanations for different failure modes with different rib conditions. On the basis of this analysis, finally, the authors discuss what should be paid attention to by the bridge management engineers.

2. METHODOLOGY

2.1 Experimental program

The steel-concrete composite deck specimens investigated here is shown in Figure 1. The in-plane dimension of the slab is 1.5 m x 1.5 m having a gross depth of 169 mm, including 9 mm thick bottom plate. I-shape steel ribs are set only in the transverse direction of 300 mm spacing. Ribs are welded to the bottom plate and any other shear connector does not exist in this deck. Reinforcing bars consisting of D10c/c250 mm in the longitudinal direction provide single RC layers on the I-shape rib, and cover depth of reinforcing bars is 42 mm. The deck is simply supported on two sides in the vertical direction.

I-shape steel ribs have different interface conditions listed in Table 1. I-300-01 has I-shape ribs with holey web. I-300-02 is a prototype. All the surface of steel was covered by Teflon sheet for I-300-03. I-300-03 implies the deterioration of initial bonding and friction mechanism because of long-term usage as a bridge deck. Loading history is listed in Table 2. First, more than 300,000 cycles pulsating load were applied. After that, simple monotonic static load were applied until failure.

2.2 Model for Analysis

The fatigue simulation by “COM3” is based on the direct path integral scheme (Maekawa et al. 2006). Simulation is conducted by tracing the evolution of microscopic material states at each moment. Logarithmic integral method accelerates computing for high cycle problem as well.

To replicate the actual stress transfer between the steel members and concrete, interface element is proposed with mechanical properties as indicated in Figure 2. The interface element considers initial bonding strength for both normal and shear direction. Once concrete and steel surface de-bond, the behavior is based upon Coulomb’s friction law. The friction coefficient is assumed to be 0.6 constant for prototype. According to Rabbat and Russell (1985), the frictional coefficient for normal strength concrete with dry condition, can be assumed to be 0.6, as a constant. The interface model does not take into account the reduction of stiffness and residual strain due to high cycle loading. I-300-01, rib with holey web, is modeled without interface element. This means complete connection of concrete and steel. I-300-03, with Teflon sheet, is modeled with interface element, which does not consider initial

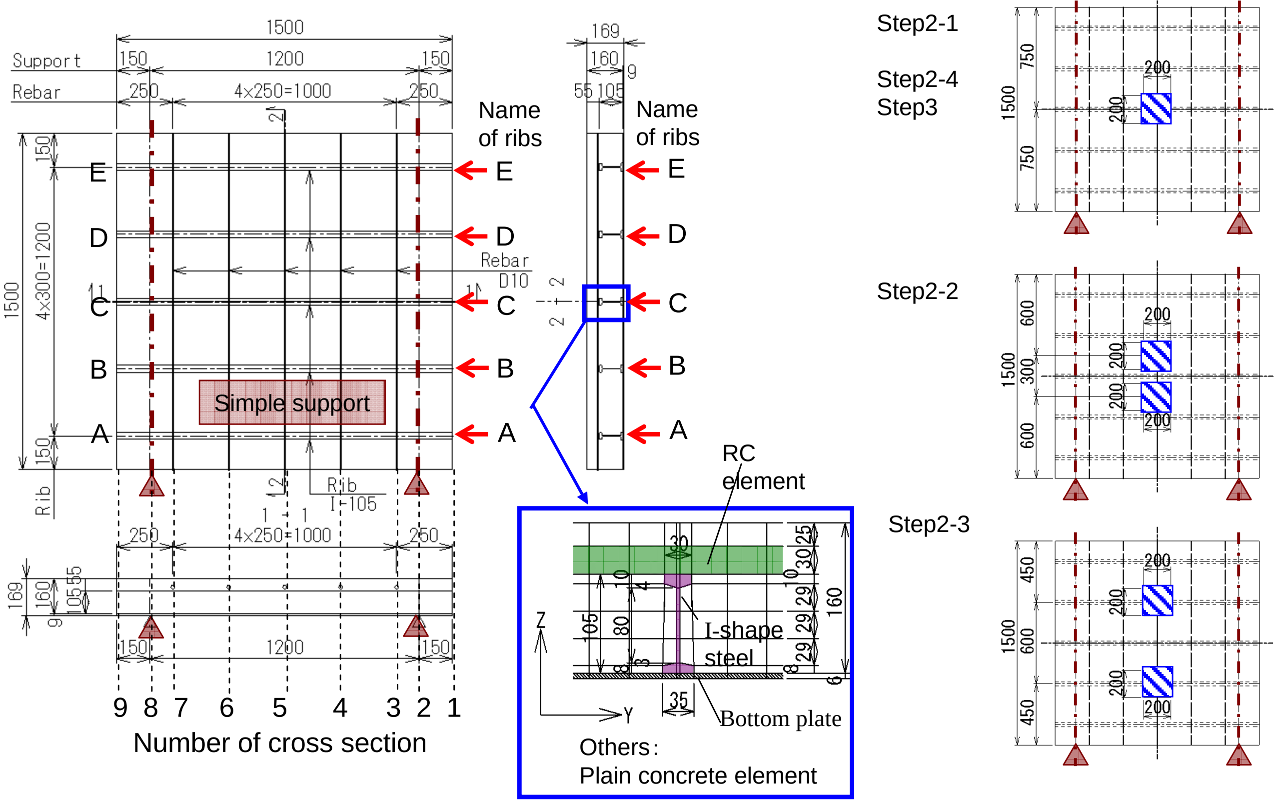


Figure 1. Specimen and location of loading point

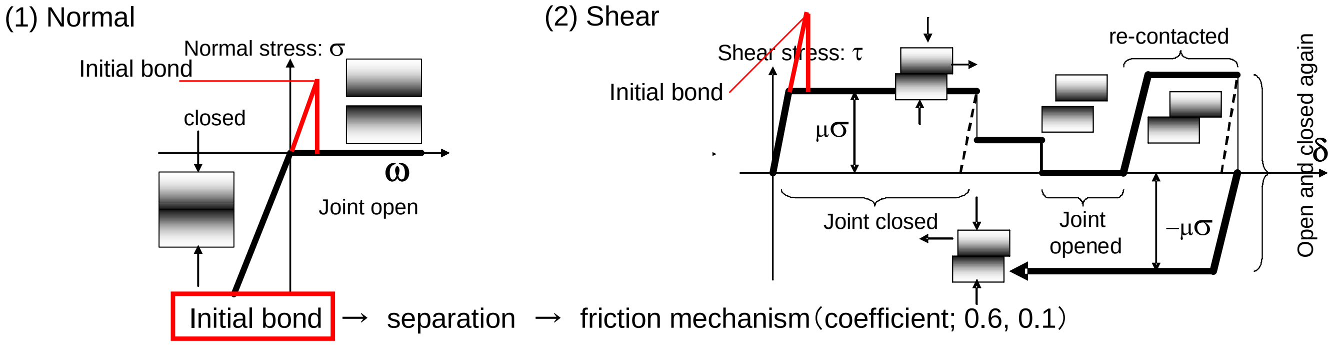


Figure 2. Interface friction model

Table 1. Experiment series

Specimen	Interface	Real ribs
I-300-01	Strong friction	Hole D50 c/c 200
I-300-02	prototype	prototype
I-300-03	Smooth	With teflon sheet

Table 2. Loading history

Step		Load (kN)	Number of cycle
2-1		120	100,000
2-2		208	100,000
2-3		226	100,000
2-4	I-300-01 I-300-02	300-400-600	10,000-1,000-100
	I-300-03	120-180-540	3-3-3
3		Until failure	1

Table 3. Material property

Spacimen	Concrete Compressive strength (N/mm^2)	Steel rib Yield strength (N/mm^2)	Rebar Yield strength (N/mm^2)	Bottom plate Yield strength (N/mm^2)
I-300-01	44.4	400	345	400
I-300-02	43.7			
I-300-03	39.3			

bonding strength. The friction coefficient is assumed to be 0.1.

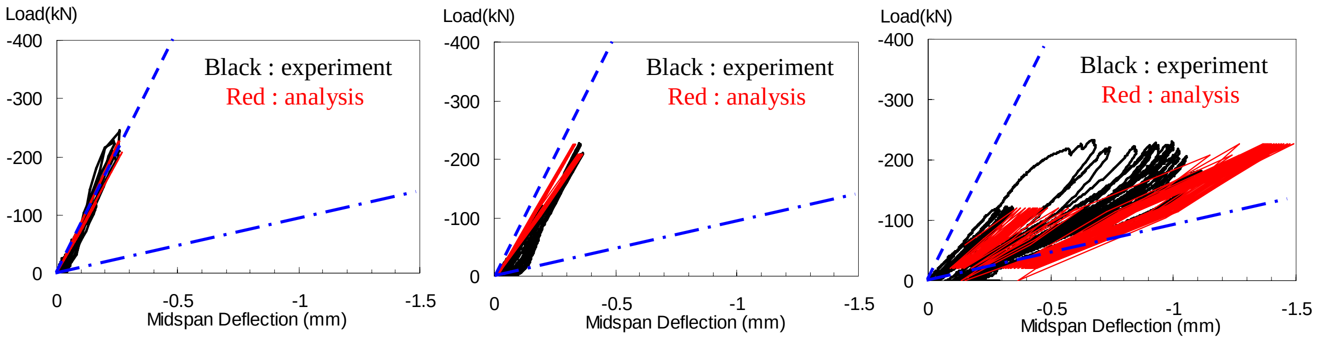
Reinforcing bars and concrete above the ribs are modeled as RC element with bond effect. The other concrete parts are regarded as plain concrete. Tension stiffening/softening factor is determined for each concrete element. Table 3 shows the mechanical properties of respective materials.

2.3 Experimental and analytical results

Load versus mid-span deflection diagrams are shown as the comparison of experiment and simulation. Figure 3 illustrates only the beginning 300,000 cycles. I-300-01 and I-300-02 shows good agreement with experimental result. Simulation shows lower stiffness than experiment for I-300-03. Figure 4 illustrates whole loading history. Simulations roughly correspond with experimental result, although post-peak performance of I-200-02 tends to be higher than experimental fact. Examined ultimate capacity of I-300-01, I-300-02 and I-300-03 in experiment are 1084 kN, 1027 kN and 644 kN respectively. I-300-03 behaves as two layer structure rather than a composite deck because of less friction interface.

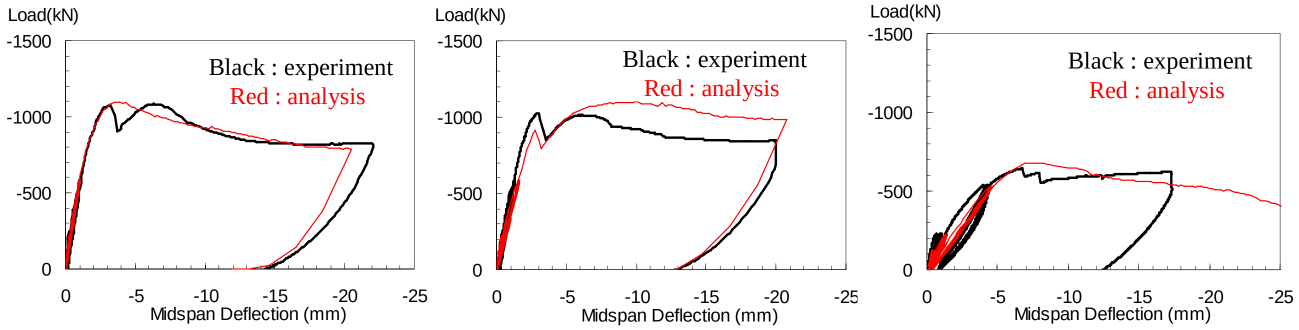
Figure 5 is a set of pictures after loading test. Band of cracks, which caused from surface concrete to bottom plate along 45 degree direction, can be observed on I-300-01and I-300-02, while the band can not be observed on I-300-03. Since concrete in this band had been crashed obviously, it is reasonable to say that the high-cycle fatigue loading might create this band. In addition, we can see another major crack that starts from the edge of loading plate and, via the tip of rib B / D, reach the root of rib A / E on all cases.

Figure 6 and Figure 7 show totally different crack patterns at the cross section transverse to the Figure 5. The crack pattern of I-300-01 is almost the same as I-300-02 (Figure 6). The crack pattern of I-300-03 is different from others. The bending crack



(a) I-300-01 (b) I-300-02 (c) I-300-03

Figure 3. Load versus mid-span deflection (beginning 300,000 cycles)



(a) I-300-01 (b) I-300-02 (c) I-300-03

Figure 4. Load versus mid-span deflection (whole loading history)

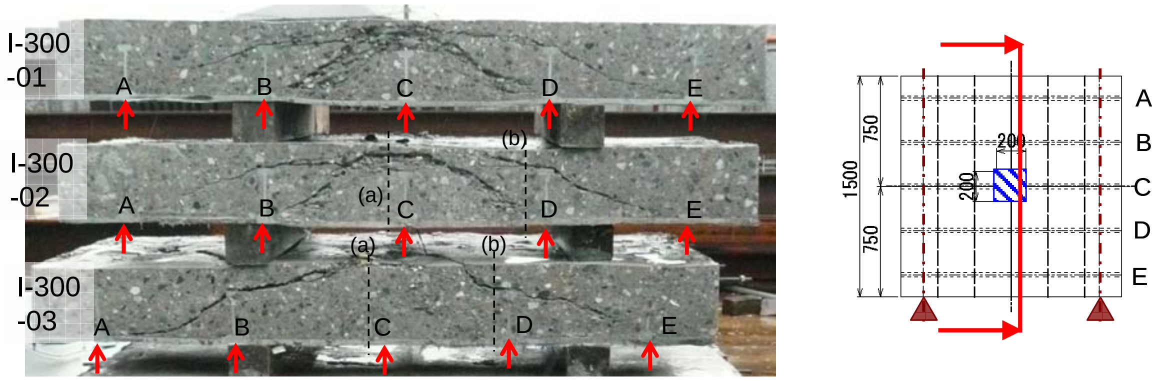
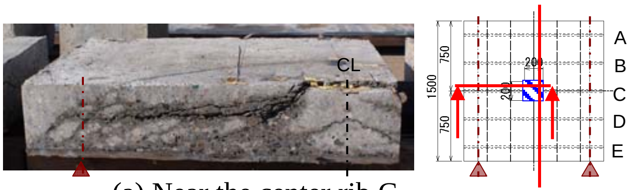


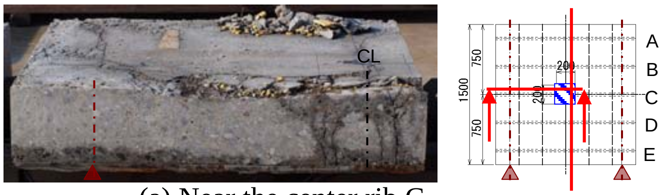
Figure 5. Cross section at mid-span (across rib)



(a) Near the center rib C

(b) Near the rib D

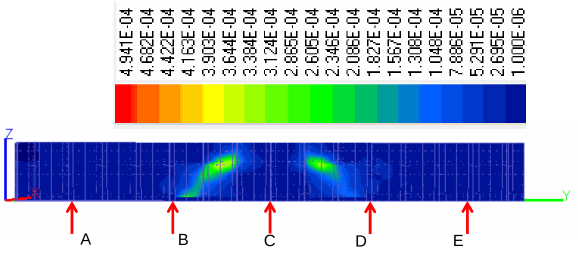
Figure 6. Cross section of I-300-02



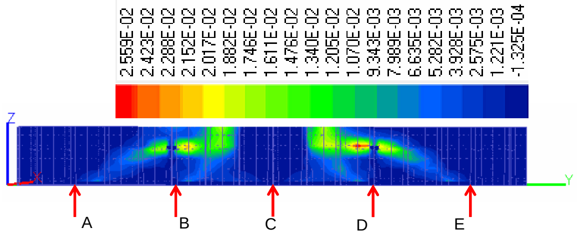
(a) Near the center rib C

(b) Near the rib D

Figure 7. Cross section of I-300-03



(a) after 311,100 cycle (Step 2-4)



(b) At peak load (Step 3)

Figure 8. Principal strain of I-300-01

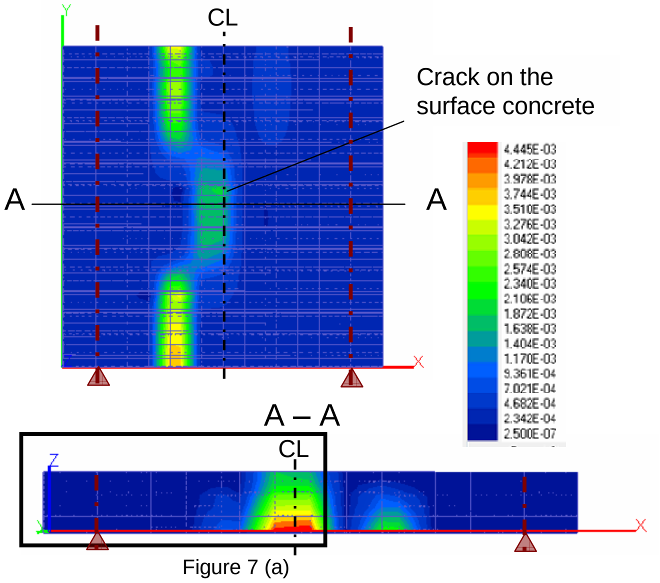


Figure 9. Principal strain of I-300-03

growing up from the bottom to the top of concrete can be observed in Figure 7 (a). Furthermore, serious cracking in the cover co ncrete above the ribs are clearly observed in Figure 7 (b).

3. DISCUSSIONS

Figure 8 (a) illustrates the principal strain at the cross section of I-300-01 after 311,100 cycle loading. The location of high residual strain area is similar to the band of crack that was observed in Figure 5. This implies that the high-cycle loading created the band in the experiment. Although the band was located on the area similar to punching shear failure crack, neither the reduction of stiffness nor the increase of deflection were not clearly observed during the procedure of high-cycle loading.

Figure 8 (b) illustrates principal strain at the ultimate capacity calculated in the analysis. The location of high strain area is similar to another major crack that was also observed in Figure 5. This implies that the increment of monotonic load created another m ajor crack in the experiment, even though the crack did not give sudden failure until steel parts completely yielded. Moreover, bottom steel plate prevents spoiling concrete. In other words, the failure of concrete is not a major matter for composite deck, as far as the concrete and steel parts maintain composite mechanism due to the bond and the friction.

In contrast, the deck, which loses the composite mechanism due to the loss of interface friction, shows different story. Figure 9 illustrates the principal strain of surface concrete and cross section of I-300-03 after 311,100 cycle loading. The severe crack of cover concrete above ribs, instead of the band of fatigue cracks, appears. The authors observed similar crack on surface concrete after 200,000 cycles during the I-300-03 experiment. It was the result of growing up of bending crack as shown in Figure 8. Crack of surface concrete is the issue that should be paid attention to by the bridge management engineer. The crack surely accelerates deterioration of concrete because of invasion of water through this crack. In addition, invasion of deicing materials cause corrosion of steel parts, and the corrosion decreases the bond between steel and concrete.

4. ASSESSMENT FOR COMPOSITE DECK

4.1 Damage index

On the basis of abovementioned study, the authors would like to call attention to the crack of surface concrete. Detection of surface crack is a suitable assessment of composite deck, because bottom steel plate prevents our crack inspection to be done from bottom side.

Another reason is that the damage progress of the composite deck is not always simultaneous with the reduction of its stiffness even if this relation is clear in the case of the reinforced concrete deck. Therefore, the monitoring of the acceleration or deflection may not be a suitable method for composite deck.

4.2 Inspection of pavement

In order to find the crack of surface concrete, periodical inspection of pavement is suggested. Cracks and pot-holes of pavement sometimes indicate damage of cover concrete.

Digital image analysis, which has been developed by a lot of researchers, can be applied for searching cracks and pot-holes. Hung et al. proposed Automated Management of Pavement Inspection System (AMPIS) (2003). They proposed the system that provides image pictures from a moving vehicle and obtained data is integrated by using GIS platform. This kind of technology may support the inspections by engineers.

3.3 Nondestructive method

If cracks and pot holes are detected by periodical inspection, engineers have to inspect in detail. That is because the detected damage might be a sign of loss of composite mechanism of composite deck. Unless the cause of damage is identified, no repair can be effective.

The purpose of detail inspection is to detect the separation of bottom plate. Mechanical sounding test is the most widely used method to examine the separation of bottom plate. Furthermore, the authors think that engineers need to identify not only separation but also damage state before separation Crack location and propagation in concrete give important information to engineers to make decision of rehabilitating and replacing based on the long-term strategy.

Nondestructive testing methods are applicable. Gassman and Tawhed successfully detected crack location and propagation of concrete bridge decks by using impact-echo method (2004). Itoh *et al.* has collected data of damage area by using acoustic emission method for composite deck (2003). In addition, radar and thermography might be applicable for detecting crack in composite bridge deck. Since those methods need not only expensive machinery but also temporary staging, detail inspection is costly. Engineers have to choose the most appropriate one.

4. CONCLUSIONS

The authors investigated structural performance of steel-concrete composite deck by using the experiments and numerical analysis. Three specimens with different interface friction between steel and concrete were prepared for this study. On the basis of this study, possible bridge assessment specially for composite deck was discussed. The main conclusions are listed as;

The failure mode of composite deck which consists of bottom plate, I-shape rib and concrete slab is strongly affected by the interface friction.

The high-cycle loading creates the band of cracks under sound bond condition. Even if the punching shear failure due to the band occurs, neither change the structural stiffness nor give the rapid increasing of deflection,

The bending crack penetrates concrete slab before forming band of cracks under the less bond condition. In other words, crack on the surface concrete is possible to be a sign of loss of composite mechanism of composite deck.

Crack on the surface concrete is a severe problem in terms of the long-term durability of concrete.

To assess composite deck, detection of surface crack is useful. Periodical inspection of pavement and detail inspection by using appropriate method are recommended.

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