MULTI-SCALE AND MULTI-CHEMO-PHYSICS ANALYSIS APPLIED TO FATIGUE LIFE ASSESSMENT OF STRENGTHENED BRIDGE DECKS

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Abstract. Reinforced concrete decks submerged in water suffer from considerable deterioration owing to high cycle repetition of traffic loads with increasing rise of inter-crack water pressure, which leads to serious damages to the top surface of concrete decks due to dropping (disintegration) of cement binder. In this study, an attempt was made to incorporate the disintegration of concrete composites into a three-dimensional multi-scale finite element analysis, which is capable of tracing the path from the occurrence of cracking to the structural out-of-plane shear failure via crack propagation. Varying fatigue life is also discussed in accordance with different states of damage at the time when strengthening work is performed. Here, the deck strengthening methods of wide variety are compared with each other.

1 INTRODUCTION

A wide variety of methods are available for strengthening non-conforming highway bridge decks in service and appropriate means are selected according to the site conditions, and both engineering and social costs [1]. Each method with its unique characteristics has proved effective in laboratory for improving fatigue durability performance. Few studies have, however, been made on the relationship between the level how seriously the deck was damaged at the time of strengthening and how long its efficiency remains. Cases have recently been reported of lost function of previously strengthened decks after the initial strengthening works [2]. Considering the magnitude of deterioration at the time of strengthening is required when discussing the applicability of a specific strengthening method. The authors conducted numerical analyses to indicate the mechanism, where the damage to decks strengthened by steel plates bonding is accelerated by corrosion of reinforcing bars in practice [3], and noted the insufficient strengthening effect being achieved in accordance with damage of existing decks.

It has been known that reinforced concrete decks subjected to moving loads suffer from double- to triple-order shortened fatigue life in the case where the top surface was submerged in condensed water than in the case where decks are exposed to mere wet states [4,5]. The phenomenon was assumed to be associated with fatigue-induced damage to concrete with increasing inter-crack water pressure [6,7], and to the damage to top surfaces of the deck due to dropping of cement binder followed by disintegration of concrete composite system with aggregate particles (Figure 1). When quantitatively assessing the efficiency of strengthening, the disintegration is thought to be of great importance. In this study, an attempt was made to incorporate the phenomenon of disintegration into a 3D multi-scale finite element analysis capable of tracing the path from the occurrence of cracking to its progress, deterioration of fatigue strength and the final structural failure [8]. Based on the simulation results, fatigue life evaluation indicated by S-N curves was obtained for decks with varying damages at the time of strengthening, and the applicability of specific strengthening methods was examined.

2 PORO-MECHANICS MODEL

It is assumed that the mechanism of disintegration in stagnant water has analogy to the deterioration of concrete due to freezing and thawing action. Damage is accumulated in concrete composite owing to repeated cycles of expansive pressure during freezing and thawing. Similarly, repeated pore water pressure excited by opening and closure of cracks propagates to a relatively large pore created at the interface between aggregates and cement paste, and the concrete composite may similarly suffer from fatigue-induced damage. The above points are taken into account in the multi-scale modeling [8] used in this study.
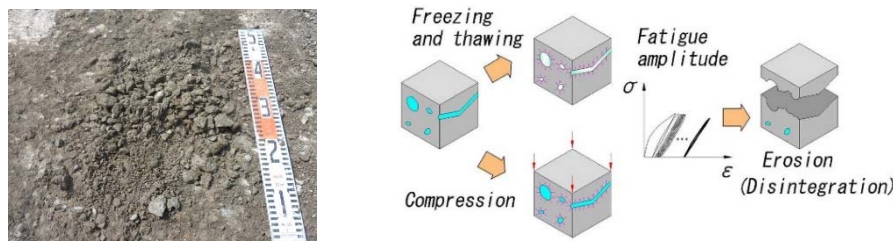

Figure 1: Disintegation of the slab [9] and modeling of concrete subjected to disintegration

Stiffness degradation with disintegration (dynamic modulus of elasticity coefficient during freezing and thawing) K is expressed by using the same equation as for the tension-induced fatigue model of concrete [8]. The pore water pressure path history is expressed by Z (initial value = 0) in a differential form with respect to pore water pressure "p" as,

$$Z = \int_{path} dZ$$

$$dZ = -10^n \cdot (1 + f_n) \cdot p_{ampl}{}^{f_n} \cdot dp$$

$$K = exp(-Z)$$

(1)

where, f_n and n are the coefficients related to the inclination and section of the S-N curve, and p_{ampl} is the amplitude of pore water pressure. With the disintegration, the bond (oneness) of reinforcement and concrete is lost. When disintegration progresses completely, $K = 0$. Then,

reinforcing bars may also lose longitudinal stiffness against transverse displacement. It is assumed that the load bearing capacity against axial compression would also deteriorate when structural concrete is disintegrated as,

$$\sigma_i = K \cdot \sigma_{ci} + \sqrt{K} \cdot \sigma_{si} \tag{2}$$

It is assumed that the mean permeability coefficient (water retention capacity) of cracked concrete element would increase at an accelerated rate as concrete is disintegrated as,

$$\kappa_{zi} = \kappa_i / Z^2 \tag{3}$$

3 FATIGUE LIVES OF DECKS WHEN THE EFFECTS OF DISINTEGRATION WERE CONSIDERED

3.1 Numerical analysis model

A reinforced concrete deck with a span of 2500 mm, longitudinal length of 3500 mm and transverse length of 2800 mm and thickness of 160 mm was examined. The specifications are typical of the decks of bridges constructed in the 1960s in Japan. The analysis model is shown in Figure 2. The symmetric model has the surface divided into two. Eight-node iso-parametric elements were used. The top flange of the main girder is modeled by using three-dimensional solid elements. Table 1 lists the conditions used in the analysis.
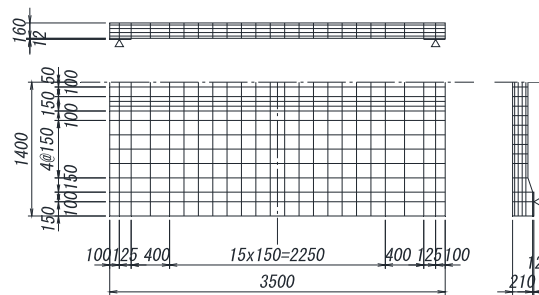

Figure 2: Analysis Model

Table 1: Material properties used in the analysis

Material	Modulus of elasticity(N/mm^2)	Characteristic value
Concrete	2.1*10^6	Compressive strength: 25.5N/mm^2 Tensile strength: 1.8N/mm^2
Reinforcement	2.1*10^5	Yield point: 355N/mm^2
Epoxy Resion	1.5*10^3	Bond Strength: 1.8N/mm^2 Shear Strength: 10.0N/mm^2

3.2 Behavior of reinforced concrete decks

Changes in deflection of non-strengthened reinforced concrete decks were verified in dry, wet and submerged conditions by conducting poro-mechanics-based nonlinear fatigue analysis, while considering the movement of condensed water through crack planes and

disintegration [5,6,7,8]. Thus, the effect of disintegration can be verified. The rate of loading was set at 3 km/h, the moving velocity in the wheel load tests using rubber tires. The load was set at 160 kN. As dry shrinkage has some impact to the deflection, the results are thought to vary according to the curing conditions [10]. In the analysis, the standard shrinkage is assumed uniformly to be 330 μ over the depth of the slab. Figure 3 shows the results.
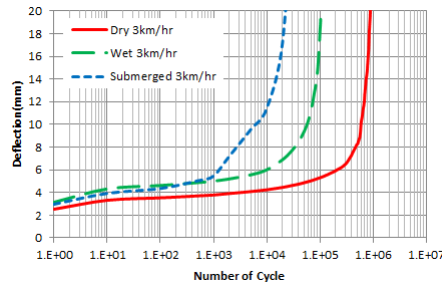

Figure 3: Deflection of reinforced concrete decks under varying environmental conditions (160 kN)

In the unsaturated condition, fatigue life is shorter in the wet condition than in the dry one by approximately a single order of load repetition. This is ascribable to the effect of water on compressive fatigue and the effect of deterioration of out-of-plane shear capacity, which is the main cause of failure [11]. In the submerged environment where fine pores are saturated with water, the phenomenon is affected by the effect of disintegration and the fatigue life is reduced by another order of load cycles. As a result, the fatigue life of the deck deteriorated by approximately double digits below the case in the dry condition as already known, in the case where the deck was subjected to moving loads [4].
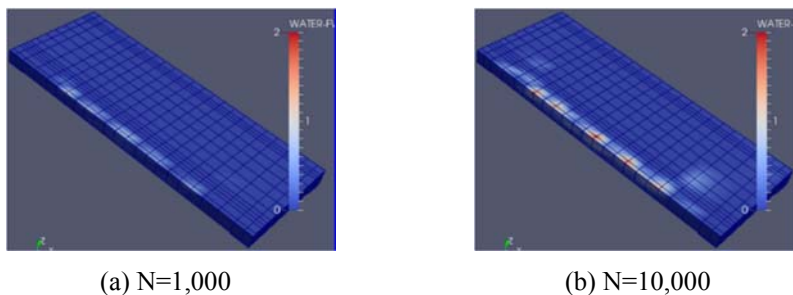

(a) N=1,000   (b) N=10,000
Figure 4: Range of disintegration (plotted using log (1 + Z))

The range in which concrete was disintegrated is shown in Figure 4. It is evident that the range expands with increasing number of load cycles. The effect of disintegration is outstanding starting from the point with 1000 times of loading at which deflection starts rapidly increasing.

3.3 Behavior of decks strengthened by steel plates bonding

On a strengthened deck, the static strength is considerably different from the pre-strengthening level and the location of the neutral axis is also different in depth. Under the same load, therefore, stresses at place by place vary before and after strengthening. The

degrees of opening and closure of cracking are also different. It was then assumed that strengthened reinforced concrete decks would exhibit different fatigue behavior from that of non-strengthened decks. Figure 5 shows progressive deflection of strengthened decks under varying environmental conditions.
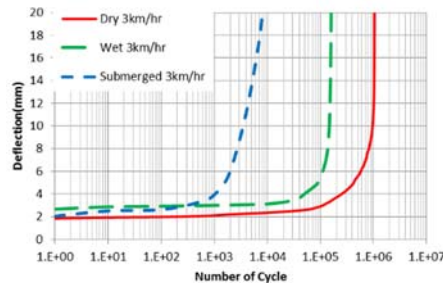

Figure 5: Deflection behavior of decks strengthened by steel plates bonding under varying environmental conditions (250 kN)

Fatigue life is shorter in the wet vapor condition than in the dry air by approximately 10 times of cyclic numbers. Especially, the fatigue life deteriorates greatly due to submerging into the stangnant condensed water. It means that the impact of disintegration caused by the condensed water is large. The considerable increase in the static capacity of the deck owing to the strengthening by steel plates bonding may lead to reduced stress amplitudes at each position. Reduction of opening and closure of cracks in concrete compression is also produced with the shifted neutral axis. Fatigue life in cycles of loading was approximately 100,000 times under a load of 250 kN. Fatigue life is shorter than in the dry condition. The effect of wet vapor environment on fatigue life is, however, relatively small at the design load level. The effect of disintegration due to submerging into condensed water is relatively large. This may be because strengthened decks suffer from the compressive flexural failure in the dry condition, because the failure of concrete in compression occurs earlier due to disintegration where the cementation of aggregate particles (Figure 1).

4 EFFECTS OF DAMAGE AT THE TIME OF STRENGTHENING ON THE STRENGTHENING EFFECTS OF DIFFERENT DECK STRENGTHENING METHODS

4.1 General

The deck discussed in this chapter is the standard one as shown in section 3.1, and main and cross girders of bridges are attached as well. The top flanges of the main and cross girders are modeled by using 3D solid elements and webs and bottom flanges are modeled by using Mindlin plate & shell finite elements. Various strengthening methods are applied and the improvement of fatigue performance is compared by conducting numerical analyses. The objective is to identify the limit of applicability of each strengthening method under the damage of different magnitudes.

4.2 Strengthening methods subjected to numerical analysis

Targeted are five strengthening methods, namely, 1) steel plates bonding, 2) carbon fiber sheets bonding, 3) increased thickness at the bottom face of slab, 4) installing additional stringers and 5) increased thickness on the top. The thickness of carbon fiber sheet was set 4.5 mm. Steel and carbon fiber sheets are numerically expressed by using the equivalent in-plane tension rigidity as indicated by the product of the elastic stiffness and the layer thickness (EA). The cross sections of different strengthening methods are shown in Figure 6.
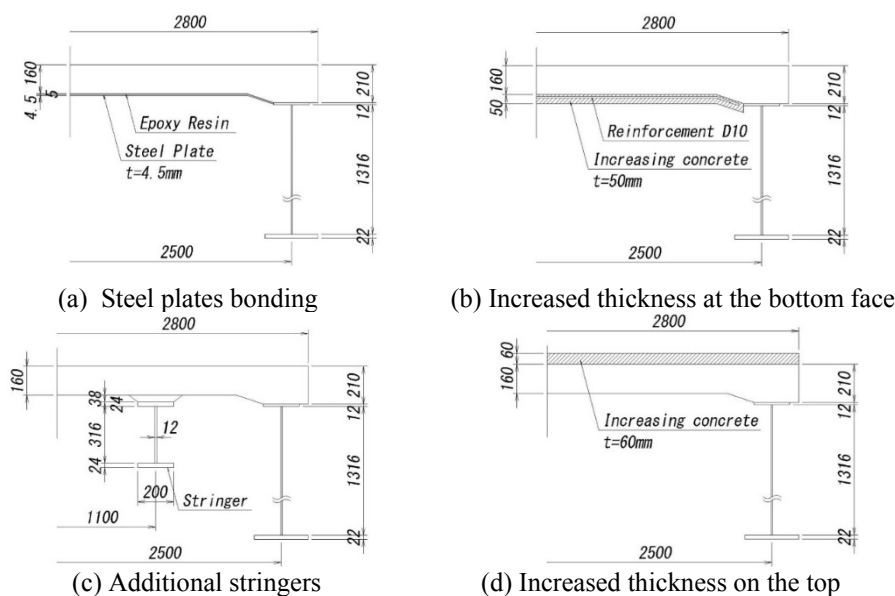
(a) Steel plates bonding

(b) Increased thickness at the bottom face

(c) Additional stringers

(d) Increased thickness on the top

Figure 6: Cross sections produced by deck strengthening methods

4.3 Damage in dry and submerged conditions

A designated number of cycles of moving loading were applied while the deck was not strengthened and then strengthening members were applied. The preliminary load while the deck was not strengthened was set 220 kN in the dry condition and 180 kN in the submerged one. Deflection at the time of strengthening is shown in Figure 7. The level of damage is assumed to correspond to the period of "progress", "acceleration" or "deterioration" stages in the order of occurrence.

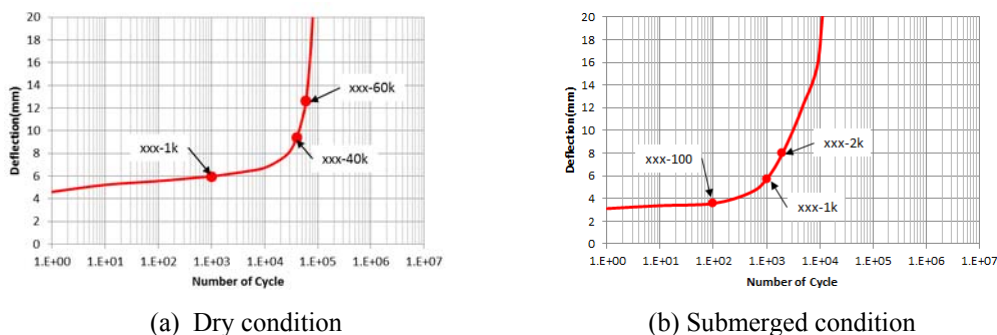(a) Dry condition

(b) Submerged condition

Figure 7: Deflection behavior of reinforced concrete deck before strengthening

This chapter takes no drying shrinkage into consideration, because changes in cracking-induced deflection ascribable to drying shrinkage can be estimated as long as the initial value is known [12], and because drying shrinkage is generally nearly discontinued when an actual structure is strengthened.

As ordinary damage to decks, spalling occurs in numerous cases owing to poor waterproofing on the bridge deck. Cement is disintegrated also in numerous cases of damage. There have recently been reports on the disintegration in compression on the decks strengthened by steel plates bonding. Then, not only the bottom face of the deck was strengthened but also the disintegrated concrete on the top surface was removed and the cross section was repaired by using ultra rapid hardening concrete in numerous cases. This chapter considers some severe conditions, and the authors discuss the cases where aforementioned strengthening methods are applied without repairing the disintegrated structural concrete while the deck is not strengthened.

5   EFFECTS OF DAMAGE AT THE TIME OF STRENGTHENING ON S-N CURVE

5.1 Steel plates bonding

Figure 8 shows S-N curves at different levels of damage in the case where steel plates are attached with chemical bonding agents for strengthening.
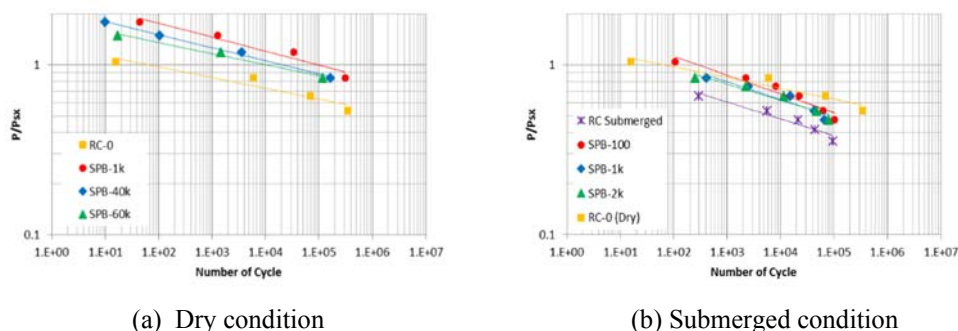

(a) Dry condition   (b) Submerged condition
Figure 8: Changes of S-N curve when steel plates were bonded

There is nearly a single order difference by the fatigue cycle life between specimen SPB-1k with the deck nearly sound at the time of strengthening and SPB-60k in which damage progressed (in the dry environment). The fatigue life is longer than RC-0 with non-strengthened reinforced concrete deck under zero loading by approximately double order of cycles even in the case where damage progresses. The method is applicable to decks where damage progresses as long as no stagnant water remains on the top of slabs.

The steel plates bonding method is applicable if the damage reach the "acceleration" stage at the time of strengthening, and can be used until the deck is affected by water [1]. The deck has a fatigue life of approximately 10^5 to 10^6 at low levels of loads. Sufficient strengthening effect was recognized on decks that nearly failed like SPB-60k. This may be because injecting epoxy resin restored stress condition of concrete in tension and because the stress of concrete in compression is extremely reduced below the case where the deck is not strengthened as the

neutral axis shifts downward in depth owing to the steel plates bonding.

The S-N curve inclines sharply in the submerged environment owing to the disintegration. The timing of strengthening affects fatigue life. In the submerged condition, fatigue life improves by approximately a single order over the life of reinforced concrete deck in all the cases. At lower levels of loads, however, fatigue life is shorter than the decks in the dry condition due to the disintegration. In the submerged environment, fatigue life deteriorates considerably. It has conventionally been explained that installing strengthening steel plates at the bottom face of the deck clogs the drainage path of storm water entering the deck, and thus affects the fatigue life. As a whole, the importance of waterproofing and drainage on the bridge deck is presented.

5.2 Carbon fiber sheets bonding

Figure 9 shows S-N curves at different levels of damage in the case where carbon fiver sheets are bonded for strengthening.
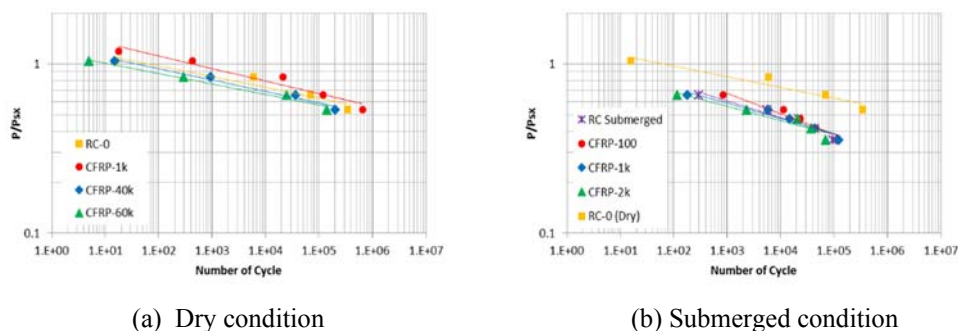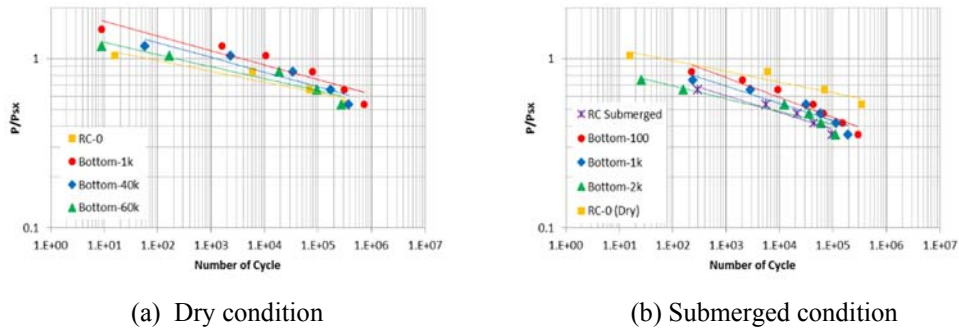

(a) Dry condition   (b) Submerged condition
Figure 9: Changes of S-N curve when carbon fiber sheets were bonded

When damage progressed, the strengthened deck has no fatigue life as long as RC-0, a non-strengthened reinforced concrete deck under zero loading. Fatigue life varies because stress amplitude is large when the carbon fiber sheets are bonded, unlike in the case of steel plates bonding. The carbon fiber sheet bonding method is said to be applicable until damage reaches the period of the "progress" stage [1]. Fatigue life did not reach the initial fatigue life of reinforced concrete decks in CFRP-40k for which damage is assumed to be in the period of "acceleration" in view of the deflection behavior (Figure 7). The strengthening effect is thus insufficient. The carbon fiber sheet bonding method is determined to be unfit for restoring the fatigue performance of decks in the case damage in progress.

Analysis shows that in the submerged environment as in the dry environment, the method is inapplicable to the deck on which damage progresses. In the submerged environment, the deck to which carbon fiber sheets are bonded is nearly the same as reinforced concrete deck in the submerged environment, if the loading level is rather low. The analysis shows that carbon fiber sheets bonding method is inapplicable in the submerged environment.

5.3 Increased thickness at the bottom face

Figure 10 shows S-N curves at different levels of damage in the case where the thickness at the bottom face of the deck is increased by constructing additional concrete for strengthening.
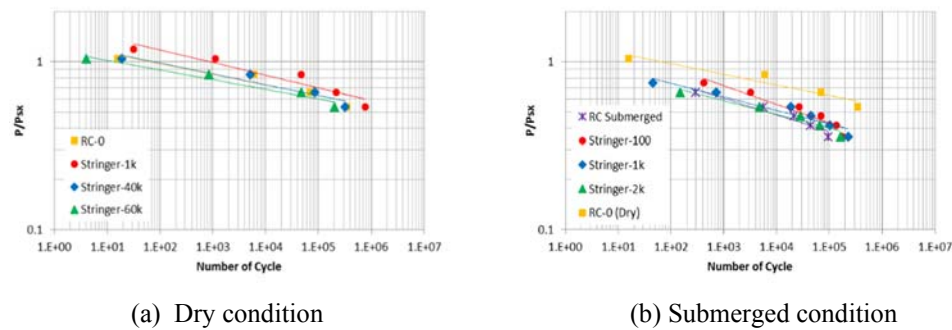
(a) Dry condition   (b) Submerged condition

Figure 10: Changes of S-N curve where the increased thickness at the bottom face of the deck

Fatigue performance is slightly upgraded than in RC-0 under zero loading in the period of deterioration. The method is applicable to decks where damage progresses. In the analysis, no attachment at the interface with an existing deck is considered. In some cases, shotcrete drops at the interface. The phenomenon will be examined in the future by numerical analysis and experiments. With the reduction of the area of reinforcement, the effect of increased thickness deteriorates. Functionally, restoring to the initially designed fatigue performance is thought to be difficult. In this analysis, sufficient area of reinforcement is assumed, which should be considered in combination with the damage to the deck. Care needs to be exercised accordingly. The increased thickness at the bottom face is applicable until the period of "progress" stage [1]. As a result of analysis in the case where sufficient area of reinforcement is applied, the strengthening effect is recognized even in the period of acceleration. The handling of interface involves some problems. Discussions have yet to be made on the expansion of the range of application.

In the submerged environment, fatigue life is similar to that of reinforced concrete deck in the period of "deterioration". Thus, no strengthening effect is recognized. Strengthening effect is found until the period of "acceleration" even under the influence of water. As in the dry environment, discussions on the attachment at the interface have yet to be conducted.

5.4 Additional stringers

Figure 11 shows S-N curves at different levels of damage in the case where additional stringers are installed for strengthening.


(a) Dry condition   (b) Submerged condition

Figure 11: Changes of S-N curve when additional stringers were installed

When damage progresses, the strengthened deck has no fatigue life as long as RC-0, a non-

strengthened reinforced concrete deck under zero loading. A stringer that is installed right below the point of loading by using the additional stringer method would be highly effective. It would become less effective if the stringer is misaligned. In this study, the most disadvantageous condition is assumed possibly on an actual bridge. The stringer is not installed right below the point of loading and may not have been so effective for strengthening the deck. In Stringer-40k, in the case where damage is assumed to be in the period of "progress", fatigue performance equivalent to the design level is achieved. In the period of "deterioration", design fatigue performance is not realized. The additional stringer method is applicable until the period of "acceleration" where the deck is free from the influence of water [1]. The location of the additional stringer has much to do with its effectiveness. The method should be applied against early deterioration up to the period of "progress".

No strengthening effect is found in the periods of "progress" and "deterioration" in the dry condition. In the area with a low level of loading, fatigue life tends to increase as compared with reinforced concrete decks submerged in water. This is because there is a change in disintegration as the span of the deck is reduced. Figure 12 shows the ranges of disintegration on a non-strengthened deck and on a deck strengthened by additional stringers.
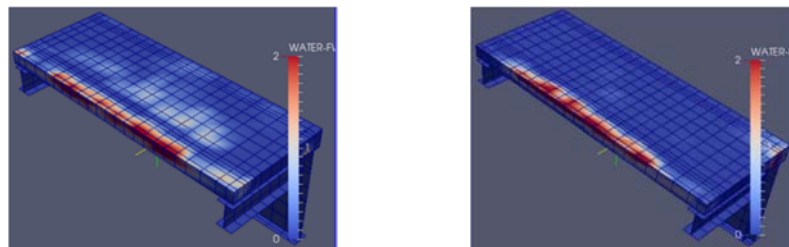
(a) Non-strengthened deck   (b) strengthened by additional stringers
Figure 12: Range of disintegration (indicated by $\log(1 + Z)$ in Equation 1)

In the analysis, Stringer-2k strengthened in the period of "deterioration" is compared with a reinforced concrete deck. The state of disintegration near the value of deflection is examined. Deflection under 120 kN is determined to be failure. On the non-strengthened deck, concrete is disintegrated in other areas than right below the point of loading. The additional stringer reduces the range of transformation. It is ascribable to the secondary effect of negative bending occurring on the stringer. The phenomenon leads to the increased fatigue life. As a result of analysis, it is shown that the additional stringer method is effective in the period of "acceleration" and where the deck is subjected to the influence of water.

5.5 Increased thickness on the top

Figure 13 shows S-N diagrams at different levels of damage in the case where the increased thickness on the top of the deck for strengthening.

The method like the steel plates bonding is found effective for improving fatigue durability sufficiently even when damage progresses considerably. The method increased thickness on the top of slabs is said to be applicable until the damage to the deck at the time of strengthening is in the period of "acceleration" and the deck is under the influence of water [1]. The method is applicable even when damage progresses in the dry condition. It should be noted that in this analysis, no attachment at the interface with an existing deck is considered.
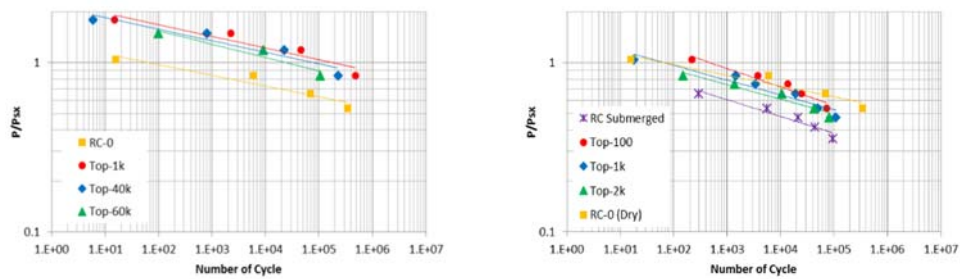
(a) Dry condition   (b) Submerged condition
Figure 13: Changes of S-N curve when the increased thickness on the top

In the submerged environment, ECC, a strengthening material, disintegrates early [13]. Care should therefore be exercised. Increase of fatigue life by a single order of cycles is recognized even in the period of deterioration. Attachment at the interface between old and new concrete should be considered in future as in the dry condition. Reports have been made on the cases where water penetrates at the old and new concrete interface and causes the top surface of old concrete to be eroded when water affects the deck [14]. Within the scope of this study, mere disintegration of the top surface of old concrete is discussed. Attachment at the interface is considered to have another impact, which will be examined in future study.

6 CONCLUSIONS

- The disintegration is generalized in structural analysis using a poro-mechanics-based solid-liquid two-phase model. The numerical analysis quantitatively shows that disintegration has a great impact on the fatigue life of reinforced deck under moving load.
- Fatigue life is shorter on the strengthened deck in the wet environment than on an ordinary reinforced concrete deck. It is shown that the fatigue life is reduced considerably when concrete is eroded with disintegration of aggregates. This corresponds to the examples of damage to existing decks.
- The applicability of existing deck strengthening methods in practical use is examined at different levels of damage to the existing deck. Early strengthening is found efficient regardless of the method. (Preventive maintenance is found important.) Certain strengthening effects are recognized on decks where deterioration progressed in the cases where steel plates bonding and increased thickness on the top methods are applied.
- Fatigue life is reduced extremely in the submerged environment below the level in the dry condition because concrete is disintegrated regardless of the strengthening method adopted. The additional stringer method is found effective because the top surface of stringer is subjected to negative loading and concrete is unlikely to be disintegrated.

7 ACKNOWLEDGEMENTS

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