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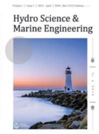

ARTICLE

Influence of Long-term Climate on Fatigue Life of Bridge Pier Concrete and a Reinforcement Method

Nam-Hyok Ri[1,2,3*] Kum-Hyok So[2] Yong-Sop Ri[2] Zhiyao Ma[1] Yong-Ae Kim[2] Hui-Gwang Yun[4]

1. School of Architecture, Tianjin University, Tianjin, 300072, China
2. Faculty of Mechanics Engineering, Kim Il Sung University, Pyongyang, DPR of Korea
3. School of Civil Engineering, Tianjin University, Tianjin, 300072, China
4. Department of Resources Exploration Engineering, Kim Chaek University of technology, Pyongyang, DPR of Korea

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ABSTRACT

This paper quantitatively evaluated the fatigue life of concrete around the air-water boundary layer of bridge piers located in inland rivers, considering the long-term climate. The paper suggests a method to predict the low-cycle fatigue life by demonstrating a thermal-fluid-structural analysis of bridge pier concrete according to long-term climate such as temperature, velocity and pressure of air and water in the process of freezing and thawing in winter. In addition, it proposes a reinforcing method to increase the life of damaged piers and proves the feasibility of the proposed method with numerical comparison experiment.

1. Introduction

The depression failure of concrete surface around the air-water boundary of bridge pier is a common damage phenomenon appears in old bridges. These concrete surface failures are caused by various factors such as construction defect, cycled fatigue loads [1,2], corrosion of reinforcement steel bar [2-5], aggressive climate change [6-8] and so on. If the factor of construction defect is excluded, the failure of bridge piers located in marine zone is mainly influenced by the accelerated corrosion of reinforcement steel bars due to the salt composition [3-5] and the failure of bridge piers located in inland zone is mainly influenced by freezing and

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**Corresponding Author:*
Nam-Hyok Ri,
School of Architecture, Tianjin University, Tianjin, 300072, China; Faculty of Mechanics Engineering, Kim Il Sung University, Pyongyang, DPR of Korea; School of Civil Engineering, Tianjin University, Tianjin, 300072, China;
Email: mech05@ryongnamsan.edu.kp

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thawing due to the temperature difference of the morning and evening in cold winter [7]. Many experimental and theoretical researches were achieved on the fatigue strength of hydraulic concretes under the ordinary or low temperature conditions [7,9]. Some experiments proved that the influence of long-term freezing and thawing due to the temperature difference of morning and evening in cold winter on the fatigue life of old bridge concrete cannot be ignored. In other words, even though the thermal stresses generated during the freezing and thawing process are not larger than the limits of static concrete strength, but it is clear that they are in the range of stress to cause low-cyclic fatigue failure of old concrete [7,9]. There are few researches on the qualitative analysis about the influence of freezing and thawing on the fatigue life of concrete pier, however, those on quantitative analysis has never been performed [6,7]. Based on these previous works, this paper analyzes the stress of old bridge concrete using the thermal-fluid-structural analysis, estimates the fatigue life quantitatively, and proposes a proper reinforcing method to increase the life of pier.

2. Materials and Methods

The case study is “Ch” Railway Bridge constructed in 1975. The diameter of piers is 4 m, the height of the tallest pier is 22.3 m. The piers No. 12 and 13 of the bridge were reinforced with non-reinforcement concrete, where no reinforcement steel bar was used, because of construction defects in 1976. After that, there occurred twice of concrete depression failures and twice of reinforced construction were performed with non-reinforcement concrete in 1988 and 2001. However, in 2014, the old reinforced layer of concrete has been damaged into the original depth again. (Figures 1 and 2 [10])

Based on the atmospheric and hydro materials in recent 10 years, the air temperature curve, wind velocity curve and water temperature curve are interpolated into various functions by MATALAB [11]. (Figures 3-5) All points in graphs are average values per day.

Table 1 shows the thermal properties and structural properties of pier concrete and reinforcement steel.

The analysis time is one year (from 1st of January to 31st of December) and the analysis objects are dynamical temperature field, fluid feild and stress field. In order to investigate the change of thermal stress due to the temperature difference between morning and evening, the time step is set to half of a day, which is the time interval between 2:00 am, when the temperature decreases to the lowest and 2:00 pm, when the temperature increases to the highest.

The river depth and flow velocity are assumed to be constant in a year, excluding the rainy season.

The average velocity of water flow is 2 m/s on the outer layer of the river flow (on the two-phase boundary of water and air (Figure 6)), and is 0 on the bottom of the river flow (on the boundary of water and ground). The liquid flow is assumed to be the Newton viscous flow, in other words, the velocity distribution is assumed to be linear from the ground to the outer layer.

In order to simulate the river flow, the Open Channel Flow is applied by VOF (Volume of Fluid) of ANSYS Fluent and the RNG k-ε turbulent flow model is used for modeling the fluid flow in the Pressure Based Solver tool.

The velocity field and the pressure field around the pier are analyzed by ANSYS. (Figures 7 and 8).

Based on the wind velocity (Figure 4) and the water flow velocity (Figure 7), the convection coefficients are calculated by the followed equations:

$$k_a = k_{an} + k_{af} v_a \tag{1}$$

$$k_w = k_{wn} + k_{wf} v_w \tag{2}$$

where k_a and k_w are convection coefficients, k_{an} and k_{wn} are natural convection coefficients, k_{af} and k_{wf} are forced convection coefficients and v_a and v_w are flow speeds of air (wind) and water (river).

The results of temperature field of thermal analysis and pressure field of fluid analysis at every step of time increment are changed into the thermal-structural boundary conditions of the structural analysis and the Drucker-Prager plastic model is used for analyzing elasto-plastic behavior of concrete in the transient structural analysis solver.

On the basis of above materials and methods, the sequential transient thermal-fluid-structural analysis is performed by ANSYS [12] and fatigue life is predicted by MATLAB.

3. Ethics Statement

The study was approved by the National Program on Key Science Research of the DPR of Korea. The work described has not been submitted elsewhere for publication, in whole or in part, and all the authors listed have approved the manuscript that is enclosed. I testify to the accuracy on behalf of all the authors.

4. Results

4.1 Fatigue Life Prediction of Sound Pier Concrete

Analysis results of temperature field and stress field of sound pier

Figure 9 is the finite element model of the sound bridge pier and Figure 10 is the temperature field and stress field at the moment of the lowest temperature in winter (at 2:00 am on January 15).

Figure 11 is the change curve of the 1st principal stress along the radial direction inside the bridge pier at the height of the air-water boundary layer and Figure 12 is the change curve of the 1st principal stress along the vertical direction on the outside surface of pier.

Figure 11 shows that the stress increases rapidly from the center to the outside surface of the pier and Figure 12 shows that the stress on the concrete surface of the air-water boundary layer changes sharply from compress to tensile. From this, it can be seen that the 1st principal stress becomes maximum on the concrete surface of the water-air boundary layer.

Figure 13 is the change curve of stress on the concrete surface on the air-water boundary layer in a year, which shows the season when the stress changes most aggressively is winter, that is, from November 15 to February 15, respectively.

Figure 14 shows the change of the 1st principal stress from November 15 to February 15 in detail.

4.2 Fatigue Life Prediction of Sound Pier Concrete

In general, the fatigue strength of the concrete increases as the temperature decreases. To predict the fatigue life, the paper uses Eq. (3), a fatigue life calculation formula of hydraulic concrete considering the effect of temperature [9]:

$$\lg N = C(t)\frac{1-S_{\max}}{1-S_{\min}/S_{\max}} \tag{3}$$

, where N is the number of load cycles and C(t) is the coefficient related to the environment such as temperature, which is generally in the range of 10 to 20. It takes 14.6 at 20 ° C and 20 at -24 ° C in case of C45 concrete. $S_{\max}$ and $S_{\min}$ are the ratios of the maximum and minimum stresses to the concrete strength in static state. Considering that C(t) is a monotonic function according to temperature and that the range of the temperature change is not large, the function of C(t) can be interpolated into a linear function of $C(t) = at + b$, where $a \approx -0.0614$, $b \approx 8.5274$. So, Eq. (3) can be rewritten as follow.

$$\lg N = (-0.0614t + 8.5274)\frac{1-S_{\max}}{1-S_{\min}/S_{\max}} \tag{4}$$

By using Eq. (4) and the graph of stress change according to the time (Figure 11), the change curve of fatigue life according to the stress amplitude per day in a year can be obtained. (Figure 15)

Figure 16 shows that the limit number of load cycles in the sound bridge pier is at least $10^{3.7}$ times (more than 70 years) under the condition that the depth and flow path of river do not change.

4.3 Fatigue Life Prediction of Reinforced Pier Concrete

The comparison between the previous reinforcing method with non-reinforcement concrete and this paper's reinforcing method with reinforcement concrete is performed. The previous reinforcing method is to reinforce the pier with non-reinforcement concrete of 80 cm thickness on the outer surface of the original damaged pier. The paper's reinforcing method is to reinforce the pier with reinforcement concrete of 30 cm thickness on the outer surface of the original damaged pier. The diameter of reinforcement steel bars is 12 mm and they placed under the depth of 5 cm from the outer surface of reinforcing layer. There are arranged 48 reinforcement steel bars in the hoop direction and 10 reinforcement steel bars per 3 m in the axial direction of the pier.

On the two reinforcing methods, the values of 1st principal stress and their changes on the outside surface of reinforced layer are similar. (Figure 16) (They are 1.5 times larger than the stress of sound pier.)

However, the fatigue lives do not equal (Figure 17). Figure 17 shows that the limit number of load cycles in the bridge pier reinforced with non-reinforcement concrete is 10^3 times (more than 15 years) and one in the bridge pier reinforced with reinforcement concrete is $10^{3.4}$ times (more than 50 years) under the condition that the depth and flow path of river do not change.

5. Discussion

The above results show that the reinforcing method with reinforcement concrete can increase the fatigue life. It is about 3.5 times more than on the reinforcing method with non-reinforcement concrete. (Figure 17)

Moreover, the reinforcing method with reinforcement concrete can reduce the effect of scouring phenomenon at the bottom of the pier, which greatly influence on the stability and buckling of the pier. The reinforcing method with reinforcement concrete can increase the safety factor against the scour phenomenon because the thickness of the reinforcement concrete layer is much thinner than one of the non-reinforcement concrete layer.

6. Conclusion

This paper quantitatively predicted the damage and fatigue life of concrete around the air-water boundary surface of bridge piers located in inland rivers, considering the thermal stress fatigue effect due to the long-term climate.

(1) The most aggressive position to the thermal fatigue of bridge pier concrete due to freezing and thawing in cold winter is the zone around the air-water boundary layer of the pier.

(2) The occurrence of fatigue cracking should be predicted in about 70 years under the condition that the depth and the flow path of river do not change.

(3) On the reinforcing method with non-reinforcement concrete, the fatigue cracking should be predicted in about 15 years under the condition that the depth and the flow path of river do not change.

(4) On the reinforcing method with reinforcement concrete, the fatigue life increases to 3.5 times (about 50 years), the safety factor against the scour phenomenon increases to 1.2 times, and the amount of required concrete for reinforcing decreases to 33 %, compared to the non-reinforcement concrete within the same strength.

Author Contributions

N. R. conceived the idea and performed theoretical calculations and numerical simulations. Y. R. supervised the project. Y. K. and H. Y. investigated the practical materials. K. S. and Z. M. contributed to preparation of the manuscript.

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Appendixes

Table

Table1. Thermal and structural properties of concrete and steel

Properties Pier concrete		Material	
		Reinforcement steel	
Thermal properties	Specific heat (J/kg/℃)	1004.8	455
	Heat conductivity (W/m/℃)	2.675	80
	Expansion coefficient (10^{-5}/℃)	1	1.1
Structural properties	Density (kg/m^3)	2470	7850
	Young's ratio (GPa)	20	200
	Poisson's ratio	0.167	0.3

Figures

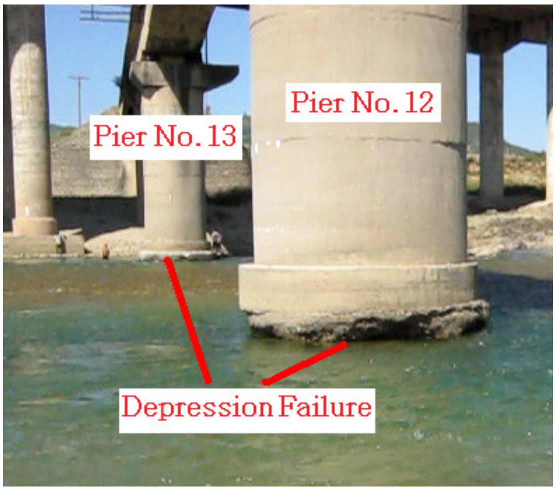

Figure 1. Damaged bridge pier

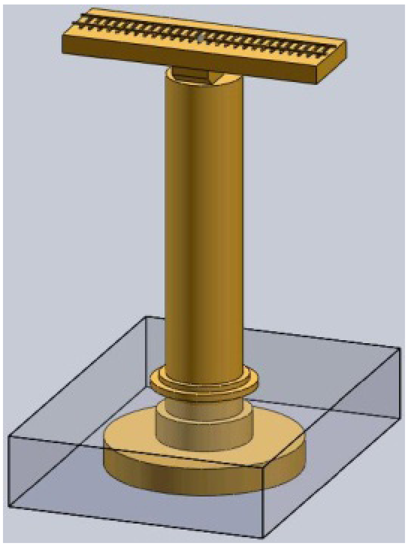

Figure 2. Geometric model of damaged pier

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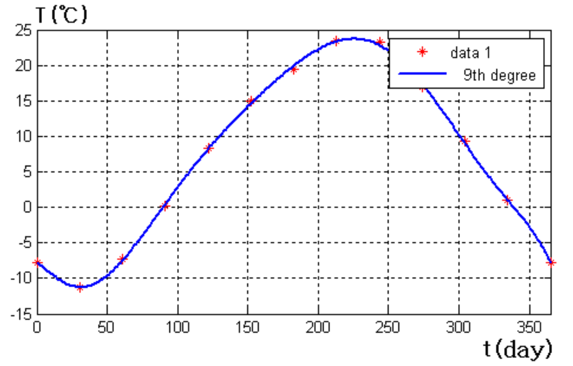

Figure 3. Daily average air temperature changes in a year

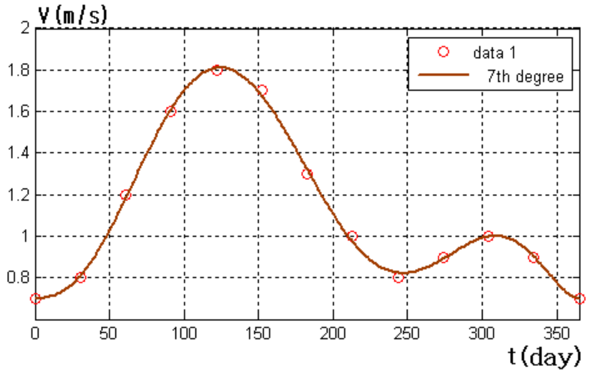

Figure 4. Daily average wind speed change in a year

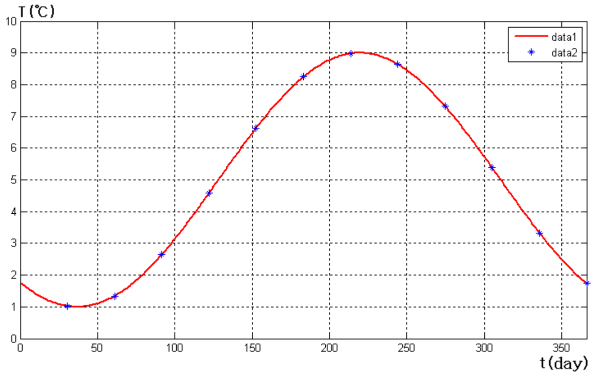

Figure 5. Daily average water temperature changes in a year

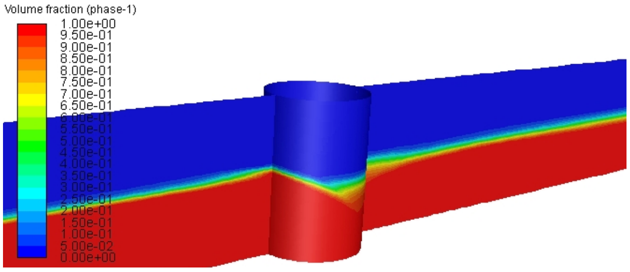

Figure 6. Volume fraction distribution on the air-water two-phase flow

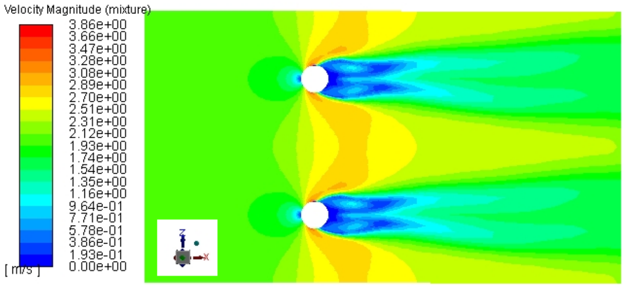

Figure 7. Water flow velocity field around the pier (on the depth of 1 m)

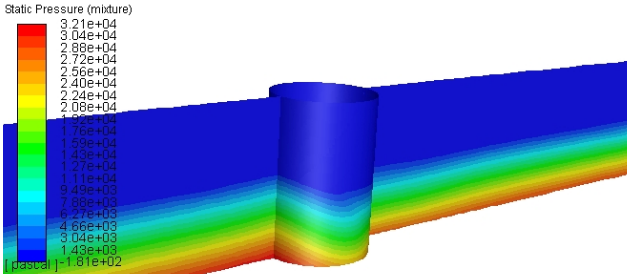

Figure 8. Water pressure field around the pier

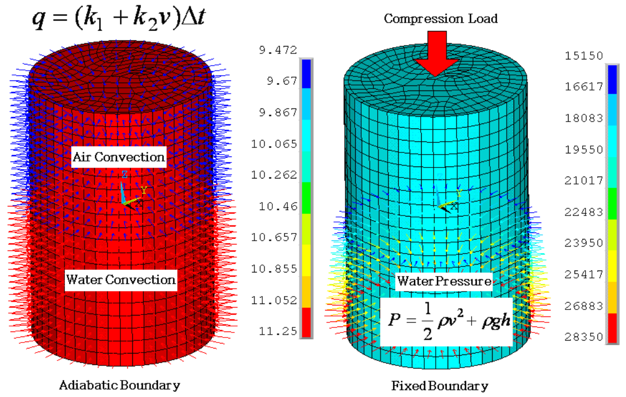

Figure 9. Finite element model

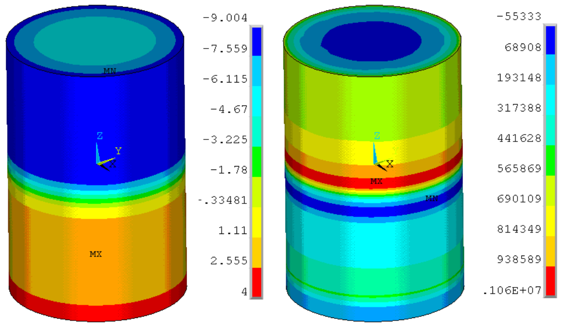

Figure 10. Temperature field and stress field of the pier

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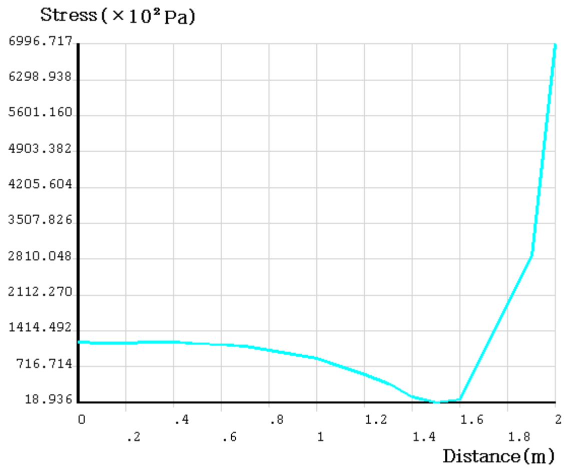


Figure 11. 1st principal stress change in radial direction

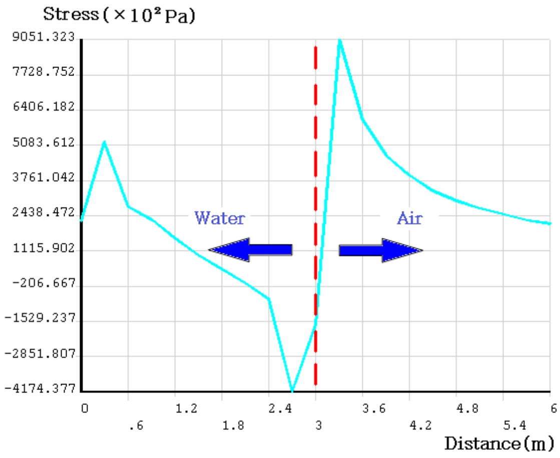


Figure 12. 1st principal stress change along the height

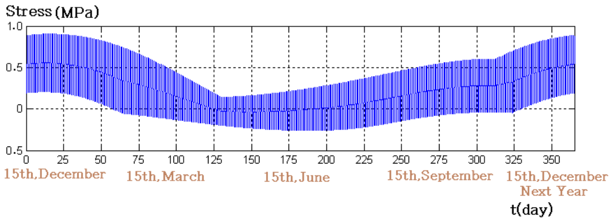


Figure 13. 1st principal stress change curve on the air-water boundary surface in a year

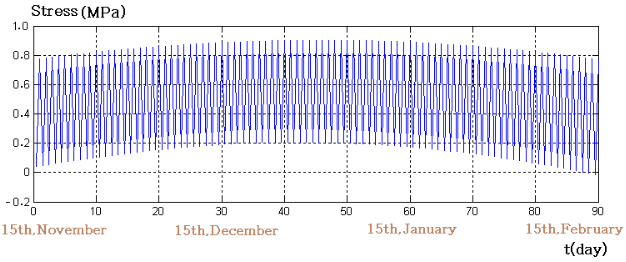


Figure 14. 1st principal stress change curve on the air-water boundary surface in winter

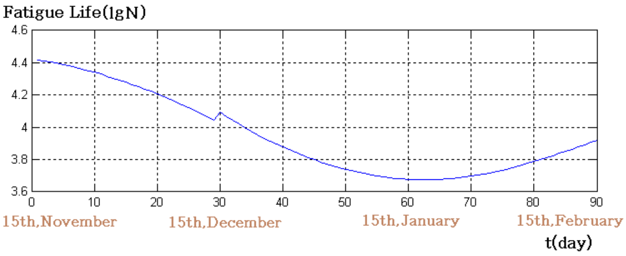
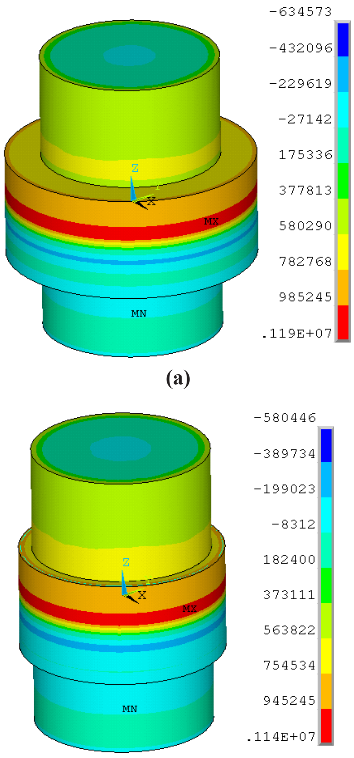


Figure 15. Fatigue life change of pier concrete according to day



(a)

(b)

Figure16. Thermal stress field of reinforced bridge piers (a: non-reinforcement concrete, b: reinforcement concrete)

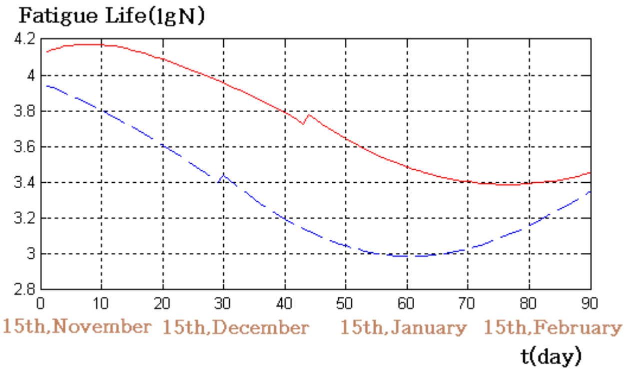


Figure 17. Fatigue life change of reinforced bridge piers (--: non-reinforcement concrete, -: reinforcement concrete)

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