LONG-TERM CONDITION MONITORING OF AFRP EXTERNAL CABLES IN A NON-METALLIC PRESTRESSED CONCRETE BOX GIRDER BRIDGE

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1. INTRODUCTION

Since the first prestressed concrete (PC) bridge, the Tyousei Bridge which was built in 1951, enormous PC bridges have been built in Japan. However, some of them have been deteriorating due to corrosion and environmental effects. Several innovative techniques have been developed to improve both the durability and structural performance of PC bridges. In 2021, the world's first non-metallic bridge, the Bessodani Bridge, as shown in Fig.1, was completed. This innovation makes PC bridges ultra-durable by eliminating the use of corrodible materials such as steel rebars and strands. The PC box girder is reinforced by 34 external cables each made of 9 ϕ7.4mm Aramid Fiber Reinforced Polymer (AFRP) rods. The use of AFRP external cables is one of the key technologies to achieve a non-metallic bridge, but the long-term condition monitoring of these external cables is a challenge because it is not possible to measure the long-term effective tension stress by strain gauge or elasto-magnetic method. This paper presents an application of the vibration method to monitor the condition of the AFRP external cables in real- time. The results of more than two years of continuous monitoring are also presented.

(b) AFRP rods (c) Opened to traffic since December 2020
Fig. 1 The Bessodani Bridge

2.MONITORING METHODOLOGY

In order to monitor the long-term performance of the Bessodani Bridge, an automated real-time monitoring system as shown in Fig.2 was installed in the bridge by Khuyen et al. (2021). The system can monitor the strain of concrete components such as the deck slab and the web concrete, the strain of AFRP rods in the butterfly web, and the strain of GFRP rebar in cable deviators by strain gauges. The segment joint is checked by measuring the relative displacement between segments in the center of the bridge using transducers. The vibration of the girder and AFRP external cables is monitored by accelerometers for real-time tracking of cable tension, bridge natural frequencies, and seismic event detection. Web cameras are also included to allow remote observation by inspectors at any time. This paper presents the two-year monitoring results of the AFRP external cable in the bridge since its completion in 2020.

AFRP rods are a composite material made of continuous aramid fibers cured with vinyl ester resin. It is a non-corrosive, high-strength material while being 6 times lighter than steel as shown in Table 1. AFRP rods are expected to alternate with PC steel strands, but it is difficult to measure the effective tension due to non-magnetic characteristics. To solve this problem, the tension in AFRP external cables is measured using an accelerometer system in the Bessodani Bridge. As shown in Fig. 2 and Fig. 3 six accelerometers, labelled as S8 to S13, are arranged to record the vibration response of the 34 external cables. Ambient vibrations and seismic vibrations are recorded in real-time at a sampling rate of 800Hz to capture the natural frequencies of the cables which are comparatively higher than that of steel cables. Data is processed in a single board computer at the sensor location every 150 seconds and then sent to the cloud system for real-time automated condition monitoring. Since the effect of cable sag and cable stiffness can be ignored, the tension T in cables is estimated by Eq. (1) where m, L, f_n, and n are cable weight, free vibration length, n^{th}-order natural frequency, and the order of calculated natural frequency, respectively Uchibori et al. (2020). The relaxation factor $\alpha(t)$ of the tension in AFRP rods is calculated by Eq. (2) where t is the relaxation time of the cable in hours. In addition to the tension in the cables, the acceleration amplitude of the cables is also observed to monitor the performance of the external cables.

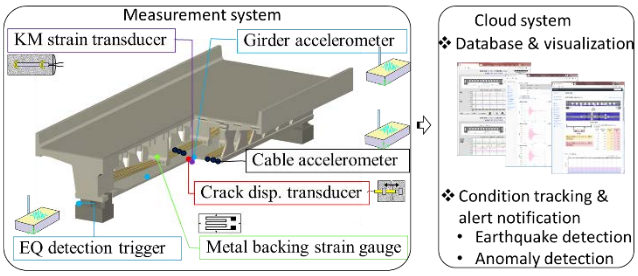
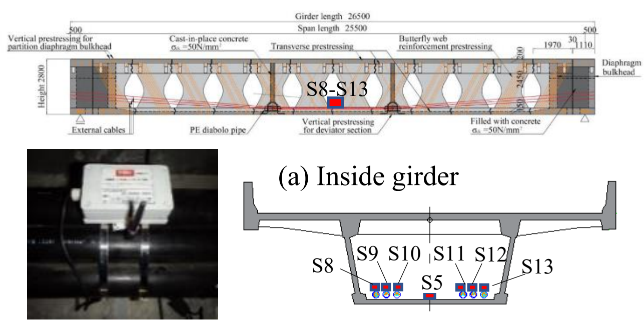


Fig. 2 Monitoring system of the Besssodani Bridge



(b) Sensor installation (c) In cross section
Fig. 3 Acceleration arrangement on AFRP external cables

Keywords: AFRP rods, cable tension, real-time monitoring, ambient vibrations, relaxation
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Table 1 AFRP ϕ7.4mm rod's properties

Name	Unit	Values
Unit weight	g/m	64±3.5
Area	mm^2	381.6
Guaranteed strength	kN	81.4
Modulus of elasticity	kN/mm^2	53±4.0
Coefficient of thermal expansion	/℃	-3×10^{-6}
Relaxation	%/1000h	14.3

$$T = 4mL^2\left(\frac{f_n}{n}\right)^2 \quad (1)$$

$$\alpha(t) = 0.95 - 0.031\log(t) \quad (2)$$

3. RESULT AND DISCUSSION

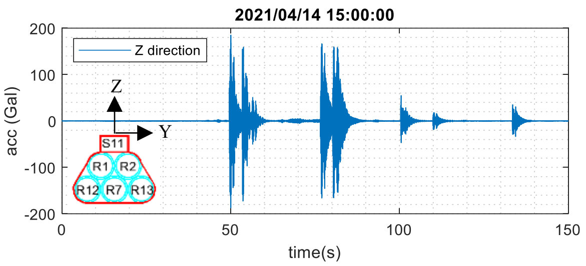

Fig. 4 Ambient vibration record in AFRP external cables

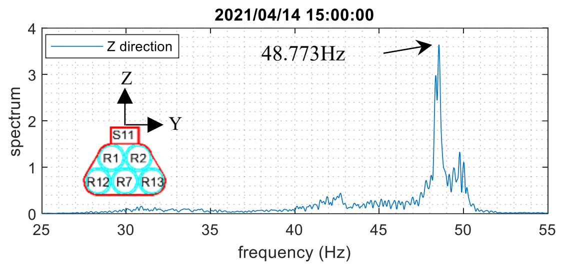

Fig. 5 Acceleration spectrum in AFRP external cables

Fig.4 shows a representative acceleration at sensor location S11 under ambient vibration conditions. As shown in Fig 3, this acceleration is the vibration of the central cables which include five tendons R1, R2, R7, R12, R13 each made of 9ϕ7.4 AFRP rods. Fig.5 shows a representative acceleration spectrum calculated from the acceleration data in Fig. 4 using Fourier transform. The first natural frequency in this external cable is 48.773Hz. Fig. 6 plots the contour plot of the acceleration spectrum over a period of more than two years. The yellow-colored part is the dominant frequency which is the first vertical natural frequency of this external cable. The tension in this case is estimated for the current effective prestress in a 9ϕ7.4 AFRP rods which represents the average tension of five tendons R1, R2, R7, R12, R13 as shown in Fig.7. This tension is the result calculated by Eq. (1) with uniform weight in 1.2237kg/m, cable-free vibration length in 5.925m. It confirms that the measured tension is consistent with the average tension which is calculated by Eq. (2) to account for the relaxation of the AFRP rods. During the two years from December 2020 to December 2022, the estimated relaxation is 10.7kN while the tension reduction measured at the S11 sensor is 10.6kN. It is also confirmed that the current effective tension in cables is higher than the design value of the effective tension when creep, shrinkage and relaxation are completed. Fig. 8 shows a change in the cable tension due to seasonal effects. It was found that during one year, the temperature changed by about 25°C, and the tension in a 9ϕ7.4 AFRP rods changed by approximately 3.5kN. Temperature is believed to be one of the causes of the change in the tension, but it is difficult to remove the temperature effect because the peak in tension has occurred earlier than temperature's peak.

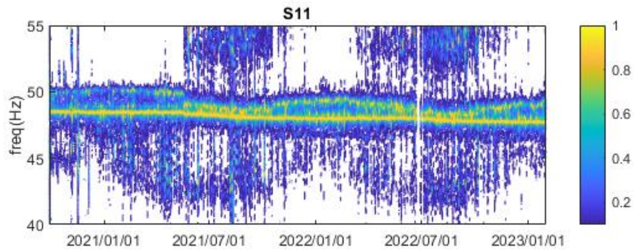

Fig. 6 Natural frequency in long term period

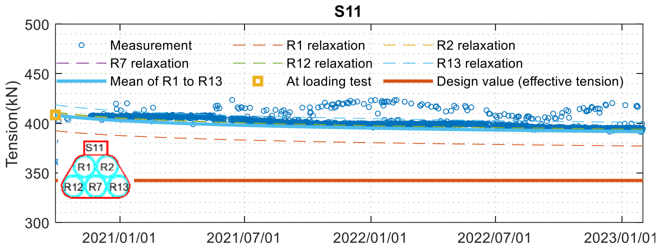

Fig. 7 Long term residual tension in AFRP external cables

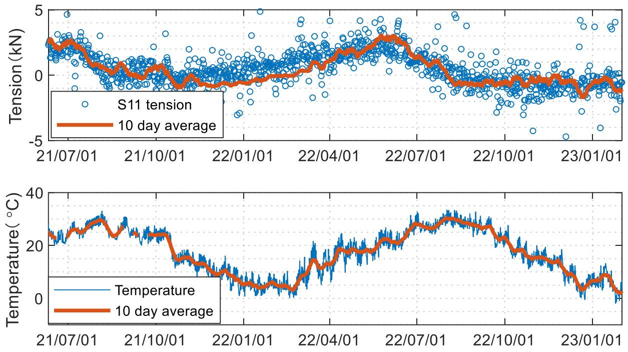

Fig. 8 Tension change due seasonal effects.

4. CONCLUSION

This paper presents a long-term condition monitoring system for AFRP external cables in a non-metallic PC bridge. Due to the nonmagnetic characteristic of AFRP rods, the vibration method was deployed to monitor the effective tension. The results showed that the accelerometers can measure the high natural frequency of the cables even under ambient vibration conditions, and the relaxation of the cables can be monitored. The tension measured over a period of more than two years showed that the effective tension was reduced by 10.7kN which is consistent with the relaxation estimated in the calculation. However, further investigation is required to remove the seasonal effect on the tension in the future.

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