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Comprehensive investigation on the cause of a critical crack found in a diagonal member of a steel truss bridge

Q. Wang, S. Nakamura *, T. Okumatsu, T. Nishikawa

Dept. of Civil and Environmental Eng., Nagasaki University, 1-14, Bukyo-machi, Nagasaki 852-8521, Japan

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ABSTRACT

Ikitsuki Bridge is a three span continuous truss bridge with a length of 800 m, which was completed in July 1991. In December 2009, a crack which seriously damages the safety of the bridge was found in a diagonal member near an intermediate pier during an inspection for determining points to be annually inspected. In order to identify its cause, some tests on the material used for the cracked member were conducted, and a long-term monitoring of wind and vibration of some diagonal members with similar structural characteristics to the cracked member had been carried out since December 2011. In this article, the outline of the crack is presented and the main causes of the crack are discussed based on the results of the tests and monitoring. The conclusions can be summarized as follows: (i) The crack initiated and propagated to become approximately 200 mm long as a fatigue crack. The quality of material and weld satisfies the requirement for them. (ii) The vibration of the diagonal members is induced by the wind with the velocity of 6–8 m/s and higher than 15 m/s in the direction approximately normal to the bridge longitudinal axis. The maximum stress range induced by the vibration due to 6–8 m/s wind is approximately 30–40 MPa, while that due to the wind blowing at the velocity of over 15 m/s can be 195 MPa. (iii) These wind-induced vibrations are thought to be the main cause of the fatigue crack.

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1. Introduction

In December 2009, a critical crack was found in a diagonal member of a three span continuous truss bridge, Ikitsuki Bridge, near an intermediate support during an inspection for determining points to be annually inspected. In order to identify the failure mode of the crack, a fracture surface observation was conducted. As a result of the observation, it was concluded that the crack was initiated and propagated as fatigue crack.

Fatigue is the progressive and localized structural damage that occurs due to repeated or fluctuating loading. It is often a major problem limiting the load-carrying capacity and the residual life of existing structures. The correct identification of fatigue-prone details in a bridge, along with well-planned inspection routines and successful strengthening and repair schedules, can guarantee the continuous and satisfactory performance of bridges during their service life [1]. Fatigue crack starts as a very small fissure and results from cyclic stresses that are below the ultimate tensile stress, or even the yield strength of the material [2]. The brittle fracture is also possible to occur suddenly from fatigue crack without any warning, which seriously damage the safety of the bridge. Wilhelm Albert devised a test machine for conveyor chains used in the Clausthal Mines and published the first article on fatigue in 1837 [3]. After that, more and more researchers and engineers have focused on the fatigue problem.

There were more than 200 fatigue and fracture cases [1,4,5] reported for steel and composite bridges, and their main causes are low temperature, stress concentration, vehicle load, and wind-induced vibration etc. Hasselt Bridge in Belgium in March 1938 and King's Bridge in Australia in July 1962 suddenly and unexpectedly collapsed in the cold weather due to brittle fracture [6]. The Silver Bridge in the U.S. collapsed in December 1967. Investigation of the wreckage showed the cause of the collapse is the failure of a single eye-bar in a suspension chain due to unstable extension or brittle fracture of two stress corrosion cracks [4]. The Sungsoo Grand Bridge in Korea collapsed in October 1994. The collapse was triggered by fatigue failure of the vertical pin-connected hanger at the north end of the suspended truss, which could be attributed to poor construction mainly related to insufficient weld penetration, and poor maintenance of the bridge under overloaded truck traffic [7,8].

Wind-induced fatigue of flexible structures is one of the important limit-state responses for structural design consideration [9].

* Corresponding author.
E-mail addresses: wangqu1989@qq.com (Q. Wang), shozo@nagasaki-u.ac.jp (S. Nakamura), okumatsu@nagasaki-u.ac.jp (T. Okumatsu), nishikawa@nagasaki-u.ac.jp (T. Nishikawa).

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Wind-induced vibrations have already caused fatigue failures in some steel bridges. In early time, some fatigue cracks by the wind-induced vibration were found in the intermediate stiffener ends of I-480 Cuyahoga River Bridge in April 1973 in the U.S., the cantilever truss vertical members of Commodore John J. Barry Bridge in March 1973 in the U.S., and the gusset ends at the diagonal member connections of Shitoku Bridge in July 1967 in Japan [5]. Although rapid progress of weld and detection technology has been made in recent years with the development of economic, unfortunately, a number of localized failures still occurred in components of steel bridges. For instance, fatigue crack was found on specific steel components and joints of a railway bridge over the Elbe River in Germany in 2000. Cyclic loads introduced in the hangers by wind-induced bending vibrations have caused significant damage involving fatigue cracking at joint welds in railway bridge hangers [10]. Fatigue crack was also found at the panel point of the diagonal member of a through-type warren truss bridge in Japan in 2007, which was caused by the wind-induced vibration of the diagonal member [11]. In addition, based on full-scale measurement of a traffic signal support structure, Zuo [12] presented an interpretation of the data collected by the monitoring system and attempted to identify the excitation mechanisms that induced the large-amplitude vibrations. Wieghaus [13] proposed a probabilistic framework to estimate the fatigue life of a lightweight, wind-excited steel structures, and compared resulting wind-induced fatigue life distributions with compiled inspection records for a large traffic signal structure population. Hong [14] and Hosch [15] observed the fatigue failure of sign, luminaire, and traffic signal support structures caused by natural wind-induced vibration and developed a comprehensive approach for fatigue design. Alduse proposed [16] a Bayesian approach to estimate the wind-induced fatigue damage of long-span bridges while considering the uncertainties in the probability model and the parameter. Repetto [17] proposed a novel approach of two levels of formulae to evaluate the alongwind-induced fatigue of slender structures and structural elements.

As described above, the cause of fatigue crack is generally heavy live load or wind-induced vibration such as vortex-induced vibration. Since the bridge site is a strait between rural islands, the traffic condition on the bridge is not severe and strong wind often blows, the wind-induced vibration was thought to be the main cause of the crack. The bridge has many members with structural and aerodynamic characteristics similar to the cracked member. Therefore, confirmation of the cause of the crack is very important to determine the appropriate countermeasure for crack prevention in other members. From this point of view, comprehensive investigation including material tests and a long-term monitoring of wind and vibration of some diagonal members with similar structural characteristics to the cracked member are carried out. This paper presents the outline of the investigation and discusses the main cause of the crack.

2. Outline of bridge and crack

2.1. Bridge

The bridge in which the crack was found is a three span continuous truss bridge, Ikitsuki Bridge with the main span length of 400 m, and the span arrangement is 200 m + 400 m + 200 m. It locates in the Hirado city, northwest of Nagasaki Prefecture, and connects Ikitsuki Island and Hirado Island, as shown in Fig. 1. It was completed in July 1991. The completion of this bridge set a new world record for the main span length of this type. The photo of the bridge is shown in Fig. 2.

Fig. 1. Location of Ikitsuki Bridge.

Fig. 2. Photo of the bridge.

The main truss spacing is 13.5 m, and the effective width of the deck is 6.5 m. There are 84 kinds of diagonal members of which the shortest one is 13.24 m long and the longest one is 23.655 m long. General layout of the bridge is shown in Fig. 3.

2.2. Crack

Large crack was found in a diagonal member shown in Fig. 4 near the north side of the intermediate support (P6) during an inspection in December 2009. As shown in Table 1, the diagonal member has a rectangular box section with the width of flange and web is 500 mm and 574 mm, respectively. The thickness of plates is 9 mm except the portion near the joints where the thickness is 12 mm. The crack on sea-side flange has the length of 465 mm and that on upper web has the length of 510 mm, as shown in Fig. 5. The crack propagated along the weld toe on the outside face of the flange. The photos of the crack are shown in Fig. 6.

3. Failure analysis

3.1. Fractographic examination of the cracked component

The fracture surface of the crack is shown in Fig. 7, and the macro fracture surface of 9 mm steel plate of the part surrounded by the red line in Fig. 7 after removing the rust by acidic solvent is shown in Fig. 8. No typical characteristics of any failure modes such as chevron pattern and beach marks were observed in the macroscopic observation. The crack face in about 200 mm from upper web is perpendicular to the surface, while other part is inclined, which suggests the difference in failure mode for these parts.

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