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Experimental investigation and numerical simulation on fatigue crack behavior of bridge steel WNQ570 base metal and butt weld

Liang Zong, Gang Shi *, Yuanqing Wang

Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- FCGR parameters and thresholds of WNQ570 base metal and butt welds have been measured.
- SDPM method is promoted and employed for deriving characteristic FCGR parameters.
- The new bridge steel WNQ570 is proved to have an outstanding fatigue resistant capacity.
- Numerical simulation by Franc3D and ABAQUS can precisely predict the fatigue life of CT specimens.

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ABSTRACT

The experimental study on the fatigue crack growth rate and the threshold of high strength bridge steel WNQ570 base metal and butt weld has been performed. Two data processing methods are conducted to derive fatigue crack growth parameters of 95% survival probability. It turns out that the fatigue crack growth rate based on each specimen data is larger than that based on group method of data processing in terms of normal stress intensity range (10–70 MPa $m^{0.5}$). The fatigue crack growth rates increase and the fatigue crack growth thresholds decrease with increasing stress ratios. For WNQ570 of the batch utilized in this research, the fatigue crack growth rate of base metal is lower than butt weld. The fatigue crack performance of WNQ570 base metal is also better than other common bridge steels including HPS485W, 14MnNbq, Q345qD and the universal steel performance provided by BS7910 and IIW-1823-07. Based on the measured FCGR parameters, numerical simulation by Franc3D and ABAQUS can precisely predict the fatigue life of compact tension specimens, which demonstrates that simulation method is appropriate to be applied to fatigue assessment practice of whole steel bridges based on linear elastic fracture mechanics (LEFM).

1. Introduction

Fatigue assessment has drawn more and more attention since 1980s [1]. Extensive researches on accurate fatigue assessment methods have been conducted by numerous scholars. Various numerical fatigue assessment methods such as hot spot stress method (HSS) [2–4], effective notch stress method [5], continuum damage mechanics (CDM) method [6,7] and linear elastic fracture mechanics (LEFM) [8,9] have been developed. Among these methods, LEFM is demonstrated to be a powerful tool to facilitate fatigue assessment due to the fact that initial cracks in real structures are unavoidable. For fatigue assessment based on LEFM, appropriate fatigue crack growth model is crucial without doubt. The typical fatigue crack growth model can be elaborated by Fig. 1 [10], illustrating the fatigue crack growth rate (FCGR) is controlled by the stress intensity factor (SIF) range at the crack front. Three different regions can be identified. Region I represents a region of quite slow FCGR, usually less than 10^{-6} mm/cycle. In addition, FCGR decreases severely as the SIF range decreases. When FCGR reaches 10^{-7} mm/cycle, the corresponding SIF range is called fatigue crack growth threshold, denoted by ΔK_{th}. If SIF range is less than ΔK_{th}, no propagation will occur. Region II represents a region of stable growth rates. For most ductile materials, region II is the control region for the whole fatigue life. Region III represents a region of unstable growth rates. If the SIF range falls into this range, the fatigue crack will propagate to rupture very quickly. Concerning fatigue life prediction, region II has a determinant influence. Region I is also taken into consideration in some researches but region III is usually ignored as the corresponding fatigue life is too short. Several formulas have been proposed to describe the relationship between SIF range and FCGR. The most

* Corresponding author. Tel.: +86 10 62797420; fax: +86 10 62788623.
E-mail address: shigang@tsinghua.edu.cn (G. Shi).

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distinguished formula is the Paris Law [11] proposed by Paris in 1963, which succinctly presented the log-linear relationship in region II. It can be given by

$$da/dN = C(\Delta K)^m$$

where C and m are the typical FCGR parameters. Besides Paris Law, there are many other formulas characterizing region I and II such as Walker formula, Forman formula [12], Hartman formula, Klesnil formula, IAB formula and so on. However, all the formulas are proposed based on the Paris Law and basically obey the Paris Law in region II. Due to the conciseness of Paris Law, it is still the most widespread principle for predicting fatigue life.

To ensure that the Paris Law can be appropriately employed in the fatigue assessment, accurate FCGR parameters are vital. These parameters can be measured by fatigue crack growth (FCG) tests. However, FCGR data of bridge steels is woefully insufficient because FCGR tests are quite costly and time-consuming. Only several grades of bridge steel have been tested, such as HPS485W [13], 14MnNbq [14,15], Q345qD [16], S355 [17], S690 [17] and so on. In addition, some design codes including BS7910 [18] and IIW-1823-07 [19] have provided universal parameters in terms of the Paris Law for steel, but the related data sources cannot be sought and the parameters given have not been verified. Generally speaking, plentiful work needs to be conducted on the measurement of the FCGR parameters for different grades of bridge steel.

WNQ570 is a new kind of low carbon bridge steel developed by Wuhan Iron & Steel Cooperation (WISCO) [20], employed in the construction of Nanjing Dashengguan Yangtze River Bridge of Beijing–Shanghai high-speed railway, as shown in Fig. 2. The bridge is one of the most important projects in the Chinese national railway construction plan, possessing three features including large-span, heavy duty (maximum axial load of main truss components up to 9000 tons) and high speed (300 km/h). Traditional bridge steel including 14MnNbq can hardly meet the design demand of the bridge. Therefore, WNQ570 is developed. The steel is classified into the grade of 420 MPa yield stress, which is viewed as Q420q according to the Chinese code [20]. As WNQ570 was successfully applied in Nanjing Dashengguan Yangtze River Bridge, its fatigue resistant capacity should be carefully investigated. FCGR parameters can represent this capacity and be employed to conduct the fatigue assessment on the bridge based on LEFM. Thus, FCGR performance of WNQ570 is thoroughly worthy being investigated.

This paper focuses on deriving the FCGR parameters of WNQ570 base metal and butt welds by experimental investigation. Typical compact tension (CT) specimens are employed in the FCGR tests. Two data processing methods are applied to ensure the reliability and confidence of the FCGR parameters. Based on the measured FCGR parameters, numerical simulation on the fatigue crack propagation of CT specimens employed in the FCGR tests is conducted based on Franc3D. It aims to verify the efficiency and effectiveness of the numerical simulation method and investigate whether it is appropriate to be applied to fatigue assessment practice of whole steel bridges based on LEFM.

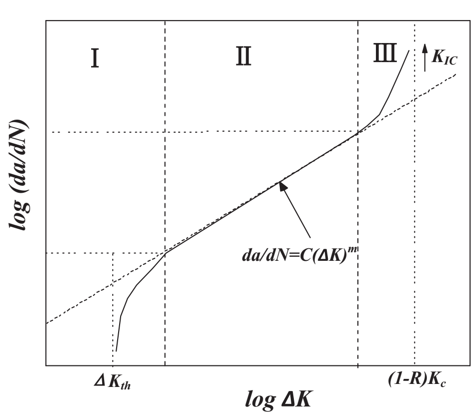

Fig. 1. da/dN vs. ΔK.

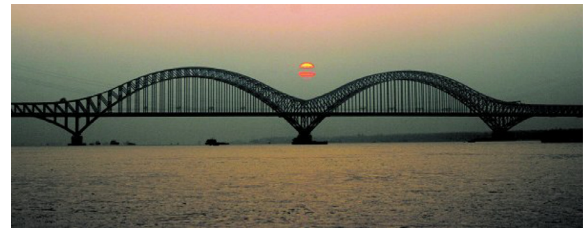

Fig. 2. Nanjing Dashengguan Yangtze River Bridge.

2. Material and experimental details

2.1. Material description

The bridge steel WNQ570 investigated in the experiment belongs to the batch employed in Nanjing Dashengguan Yangtze River Bridge, produced by WISCO. The nominal thickness of all the steel plates is 12 mm and the measured thickness is 11.6 mm. Half of the plates are welded by MCAW using WER60 welding wires, which are also produced by R&D in WISCO. The diameter of the welding wires is 1.2 mm and the average size of the weld beads is about 4–5 mm. The joint preparation is presented in Fig. 3. Two weld beads were filled into the one-sided groove. All the welds have been inspected by NDT according to related Chinese provisions [21] and proved to be qualified. The factors that influence the fatigue behavior of the welds contain the welding process and the post treatment after welding. The welding process has a great effect on the quality of the welds, such as the microscopic structure, grain size and grain direction. In addition, the post treatment after welding, such as heating, hammering, will improve the fatigue behavior of the welds. No post treatment was performed for the butt welds used in this test.

Before the FCGR test, basic mechanical properties of the WNQ570 base metal and butt weld were measured through uniaxial tension, employing three replicates, respectively. All the tensile specimens are snapped finally. The percentage elongation after fracture A and the percentage reduction of area Z are measured. All the results are recorded in Table 1 and meet the mechanical requirements specified in GB/T 714-2008 [22]. The investigated stress vs. strain relationship is shown in Fig. 4. For WNQ570 base metal, a short yield plateau can be identified, while, no plateau for WNQ570 butt weld was observed. It is shown that the WNQ570 steel plates used in this research shows a higher yield strength than 460 MPa and can be viewed as a kind of high strength steel. In addition, the weld metal overmatch is applied in the specimens of our tests, which means the strength of the pure weld is larger than the strength of parent material.

The chemical composition of WNQ570 base metal and butt weld are investigated by Thermo Scientific ARL 4460 optical spectrum analyzer, recorded in Table 2. As for the base metal, the carbon equivalent CEV is 0.42% and the crack sensitivity coefficient Pcm is 0.18% obtained according to GB/T 714-2008 [22]. Both the two parameters indicate WNQ570 base metal is of good weldability. In addition, the chemical composition of the butt weld is similar to that of the base metal in terms of the five main elements including C, Si, Mn, P and S, which proves the weld wires can match the base metal commendably.

The microstructures of WNQ570 base metal, HAZ and butt weld are observed using an optical microscope, as shown in Fig. 5. The base metal shows a typical microstructure of bainite. The average grain size is about 5–10 μm. For HAZ, the microstructure is a mixture of spicule and bainite of 5–10 μm average size. The microstructure of the butt weld is a mixture of bainite, ferrite and pearlite and the corresponding grain size is smaller than base metal and HAZ.

2.2. FCG testing details

The FCG tests were performed using CT specimens, based on the procedures specified in the ASTM E647 standard [23]. The normal profile of CT specimens is presented in Fig. 6a. However, the notch of the CT specimen employed in this

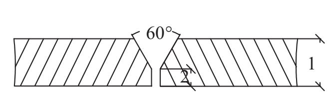

Fig. 3. Profile of welded joint preparation.