Fatigue Crack Growth Rate Tests of High Performance Steel HPS 485W

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Abstract Research in this paper is about fatigue and fracture behavior of high performance steel HPS485W produced in Wuyang Steel Factory in China. Fatigue crack growth rate (da/dN) test was conducted for HPS 485W compact specimens with thickness of 7.5mm, 12.5mm and 19.5mm under different fatigue load ratio ($R=F_{min}/F_{max}=0.1$, 0.5 and 0.8), respectively. The seven-point incremental polynomial method was adopted for local fitting to obtain fatigue crack growth rate. The test results show that HPS485W has better crack growth resistance compared with traditional steel 14MnNb. What's more, specimen thickness is an influencing factor for crack growth rate, and fatigue crack growth rate increases with the increase of fatigue load ratio R. For 19.5mm specimen under fatigue load with R=0.1, the engineering threshold was tested and numerical calculation was conducted to obtain theoretical threshold. The calculated theoretical threshold is $7.22\text{MPa.m}^{0.5}$. Fatigue life of high performance steel bridge can be predicated based on tested fatigue crack growth rate curve. Study in this paper serve as test basic for the fatigue control and fracture control of high performance steel bridge.

Keywords high performance steel, fatigue crack growth rate, stress intensity factor, threshold value, fracture

1. Introduction

High performance steel (HPS) for highway bridges was developed, which has superior characters in strength, weldability, toughness and corrosion resistance. Compared with steel bridge fabricated by traditional steel, these material characters bring several advantages to HPS bridges such as longer span length, easier fabrication, greater crack tolerance, elimination of painting in operation stage and so forth [1, 2]. Nowadays, about 250 HPS bridges have been constructed in the U.S., and all of these HPS bridges have demonstrated to be structural efficient and economical in whole life cycle [1]. So, the construction of HPS bridge is an attractive choice for modern society. However, with assumption that HPS detail has the same fatigue performance as conventional structural steel, effectively use of HPS may not be possible when fatigue limit state controlling the design [3].

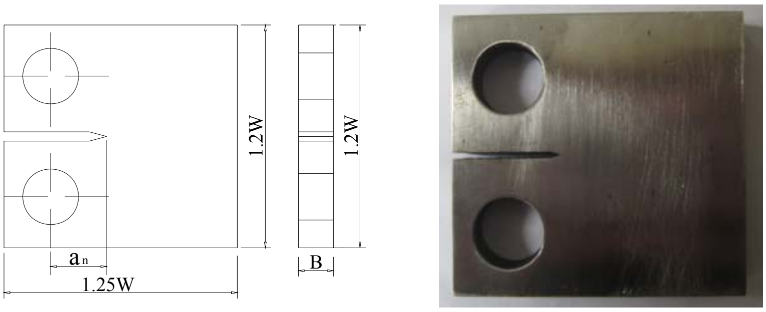
Fatigue and fracture are typical failure mode for steel bridge. With purpose of ensuring high performance steel bridge operation safety, fracture failure control and remaining fatigue life calculation should be studied clearly. Thus, it's necessary in this paper to carry out study for fracture toughness and fatigue characters study for high performance steel Q&T HPS 485W, which is produced by Chinese Wuyang Iron and Steel Co., Ltd. [4]. In this paper, with purpose of remaining life calculation and safety assessment, fatigue crack growth rate test was conducted under different load ratio to acquire fatigue crack growth parameters by Paris equation under cyclic loading, and threshold value was also tested and calculated. The test study in this paper provide important parameters in high performance steel bridge fracture control design and its remaining fatigue life calculation.

2. Fatigue crack growth rate test

Fatigue crack growth rate (da/dN) tests were conducted to determine the fatigue crack growth rate according to ASTM E647-08 and referencing to Chinese GB/T 6398-2000 [5, 6].

2.1. Test specimens

d*a*/d*N* tests were conducted for compact specimen [C(T)] with different HPS 485W thickness under load ratio of R=0.1, 0.5 and 0.8. The prefabricated crack for all the specimen is oriented perpendicular to the rolling direction of the steel plate (L-T). The dimension and specimen are shown in Figure 1 and Table 1.



(a) Dimension of C(T) specimen (b) Fabricated C(T) specimens

Figure 1. Dimension of C(T) specimen

Table 1. Specimens dimensions (mm)

B	$1.25W$	$1.2W$	a_n
7.5	50	48	9
12.5	75	72	15
19.5	125	120	23

The loading frequency during test is 15 Hz, considering low frequency of the alternating cycle load in practical traffic transportation. Fatigue crack precracking is conducted before test to provide a sharpened fatigue crack. During the test, the electro-hydraulic servo-controlled fatigue testing machine was used and the crack growth length is read by the microscope with min scale of 0.01mm. The load cycle number and corresponding crack length are recorded at certain intervals from near-threshold to fatigue crack propagate unstably.

2.2. Test result

After the test, the stress-intensity factor range ΔK_i under each crack length is calculated, according to Eq.1. In Eq. 1, $\alpha = a/W$ 错误！未找到引用源。, and $a/W \geq 0.2$.

$$\Delta K = \frac{\Delta P}{B/W}\frac{(2+\alpha)}{(1-\alpha)^{3/2}} \cdot (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (1)$$

Using Paris equation to fit tested ΔK_i and $(da/dN)_i$ data. The parameters are obtained including material constant m and C, the standard deviation S, and correlation coefficient. The d*a*/d*N* test result for HPS 485W is shown in Table 2 and Figure 2.

The fracture surface of d*a*/d*N* specimen presents fibrous, and grey or dark grey. Figure 3 shows fracture surface for one of test specimens. The fatigue fracture is composed with crack propagation phase and ultimately quickly failure phase, corresponding to smoothing region and intense coarse region. The fracture surfaces of specimens, shown in Figure 3, are characterized with secondary cracks. The fracture surface has strong stereoscopic impression.

Table 2. Fatigue crack growth rate of Q&T HPS 485W steel

Thickness	R	Regression Parameters				
		m	C（m/cycle）	log$C$	Correlation coefficient	S
7.5mm	0.1	2.84	1.05×10^{-11}	-10.98	0.96	0.06
	0.5	4.13	2.37×10^{-13}	-12.62	0.97	0.05
	0.8	3.26	3.64×10^{-12}	-11.44	0.96	0.05
12.5mm	0.1	2.53	2.19×10^{-11}	-10.66	0.87	0.12
	0.5	2.72	1.48×10^{-11}	-10.83	0.84	0.11
	0.8	3.16	6.11×10^{-12}	-11.21	0.73	0.1
19.5mm	0.1	3.28	2.29×10^{-12}	-11.64	0.99	0.05
	0.5	3.29	2.82×10^{-12}	-11.55	0.98	0.05
	0.8	3.29	3.24×10^{-12}	11.49	0.99	0.05

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(a) Test result for 7.5mm specimen (b) Test result for 12.5mm specimen

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(c) Test result for 19.5mm specimen

Figure 2. log(da/dN) and log(△K) curves for HPS485W specimens

2.3. Threshold value test

Threshold value (ΔK_{th}) is a significant factor in fracture control design of steel structures and load decreasing procedure is used for ΔK_{th} test. ΔK_{th} for 19.5mm HPS 485W specimen under R=0.1 is tested and the test result is shown in Figure 4 [7]. The calculated theoretical threshold value is 7.22MPa•m$^{0.5}$.

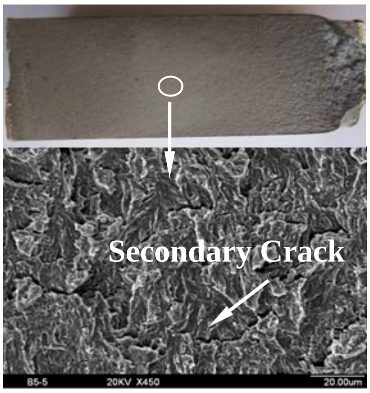

Figure 3. Fracture surface of specimen

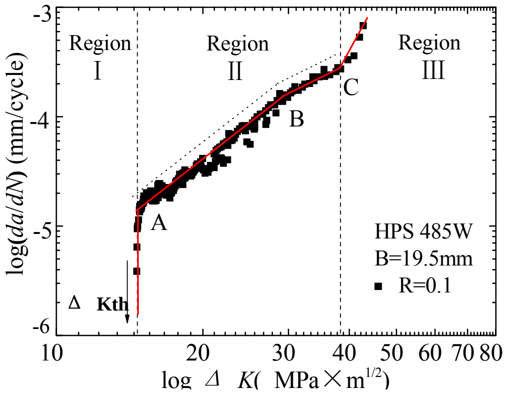

Figure 4. log(d*a*/d*N*) and log(△*K*) curve for 19.5mm specimens

3. Test result analysis

Ren et al. conducted d*a*/d*N* test for 24mm, 32mm and 50mm 14MnNb steel under load ratio of *R*=0.1, 0.2 and 0.5 [8]. The test result of Ren Weixin is shown in Table 3. Neglecting thickness effect, compare d*a*/d*N* test result of HPS 485W and 14MnNb was conducted. For *R*=0.1, the tested *m* is ranging from 2.53 to 3.28 and *C* is ranging from 2.29×10^{-12}m/cycle to 2.19×10^{-11}m/cycle for HPS 485W, while the tested *m* is ranging from 2.67 to 3.74 and *C* is ranging from 5.83×10^{-10}m/cycle to 1.98×10^{-8}m/cycle for 14MnNb. For *R*=0.5, the tested *m* is ranging from 2.72 to 4.13 and *C* is ranging from 2.37×10^{-13}m/cycle to 1.48×10^{-11}m/cycle for HPS 485W, while the tested *m* is ranging from 3.39 to 4.08 and *C* is ranging from 3.08×10^{-10}m/cycle to 1.76×10^{-9}m/cycle for 14MnNb. Learn from comparative result, the tested value of m is similar for traditional bridge steel 14MnNb and HPS 485W, which is about 3. However, the tested value of *C* for HPS 485W is much smaller than 14MnNb. Fatigue crack growth rate is increasing with the increase of *C* and *m*, so compared with traditional 14MnNb, HPS 485W has superior fatigue crack resistance.

The average value of m in Table 3 is 3.17. Using this average value of m=3.17, the log(d*a*/d*N*) and log(△*K*) curves are re-fitted by Paris equation for HPS485W specimens. The re-fitting test result is shown in Table 4. The correlated coefficient in Table 4 means the derivation from average value for all the HPS 485W specimens. Learn from Table 4, firstly, for the same load ratio *R*, thickness of specimen has obvious affection for fatigue crack propagate rate. Secondly, for specimen with same thickness, with the increase of *R*, value of *C* is increasing, which means fatigue crack growth rate is increasing.

Table 3. d*a*/d*N* test result for 14MnNb

Thickness	*R*	Regression Parameters		
		m	*C*（m/cycle）	Correlation coefficient
23.5mm	0.1	3.59~3.74	5.83～8.38×10^{-10}	0.97～0.99
	0.2	3.31~3.72	6.55×10^{-10}～ 1.31×10^{-9}	0.97～0.99
	0.5	3.81~3.97	3.83～5.39×10^{-10}	0.97～0.99
31.5mm	0.1	2.67~2.91	1.02~1.98×10^{-8}	0.99
	0.2	3.45~3.52	1.01~1.62×10^{-9}	0.99
	0.5	3.39~3.75	4.81×10^{-10}~1.76×10^{-9}	0.95~0.99
49.5mm	0.1	2.97~3.24	2.87~6.43×10^{-9}	0.99

	0.2	3.16~3.33	2.25~4.29×10^{-9}	0.99
	0.5	3.58~4.08	3.08~9.28×10^{-10}	0.99

Table 4. Re-fitting result after HPS 485W da/dN test

Thickness	*R*	Regression Parameters			
		m	*C*（m/cycle）	log*C*	Correlation coefficient
7.5mm	0.1	3.17	3.71×10^{-12}	-11.43	0.91
	0.5	3.17	4.58×10^{-12}	-11.34	0.87
	0.8	3.17	4.65×10^{-12}	-11.33	0.93
12.5mm	0.1	3.17	2.85×10^{-12}	-11.54	0.82
	0.5	3.17	3.95×10^{-12}	-11.4	0.61
	0.8	3.17	5.24×10^{-12}	-11.28	0.61
19.5mm	0.1	3.17	2.95×10^{-12}	-11.53	0.83
	0.5	3.17	3.85×10^{-12}	-11.41	0.96
	0.8	3.17	4.20×10^{-12}	-11.38	0.95

Zhang et al. conducted d*a*/d*N* test for 24mm 14MnNbq at room temperature by three-point loading specimen, which is applied in steel and concrete composite railway bridge in Qinghai-Tibet railway system [9]. For 14MnNbq base steel, the tested parameters in Paris equation is C=1.4763×10^{-10}m/cycle and m=2.1413, which shows HPS 485W has greater fatigue crack growth resistance than 14MnNbq. The comparative results demonstrate better fatigue resistance of HPS 485W.

4. Conclusions

This paper conducted fatigue crack growth rate (da/dN) test to study fatigue resistance of high performance steel HPS 485W. The d*a*/d*N* test result shows HPS 485W has better fatigue crack growth resistance than traditional steel. The fatigue crack growth rate of HPS 485W is determined by Paris equation, which provides significant parameters in remaining fatigue life calculation of HPS bridge. Research in this paper demonstrates HPS 485W has superior fatigue resistance, and HPS 485W is suggested to be prior used in stress complex part of steel bridge.

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