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Retarding effects on crack propagation by closing crack surface using ICR treatment

YuanZhou Zhiyuan, Ji Bohai *, Fu Zhongqiu, Sun Tong

College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China

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ABSTRACT

The impact crack-closure retrofit (ICR) treatment was applied to cracked specimens. Two fatigue test stages were applied: the first stage was designed to prefabricate the fatigue crack, and the second stage was used to evaluate the retrofitting effect by assessing fatigue life. The stress was monitored through strain gauges during the fatigue test, and the stress intensity factor (SIF) at the crack tip was determined by a two-strain-gage technique. The extended finite element method (XFEM) was adopted as a means of acquiring the stress in each specimen, or the SIF, where it is difficult to measure it during the fatigue test. The test results show significant improvement on the delay of crack propagation due to the ICR treatment, as well as the fatigue resistance within cracked areas. Moreover, the cracked section is enhanced when closing the crack surface through the comparison of the stress variation with, and without, crack closure. The SIF at the crack tip decreased by about 36%, slowing down the crack growth rate, according to the fracture mechanics due to the change of crack profile and stress redistribution.

1. Introduction

Fatigue damage cases in steel bridges have been reported in recent years, raising growing concern by engineers. Fatigue is usually the cause for the crack emanating at bridge components in service, and is affected by various factors, such as: material deterioration, environmental conditions, and repeated heavy traffic loading [1–4]. The propagation of cracks will lead to structural fracture in most cases, causing partial or total structural deficiency. An increasing need for effective rehabilitation approaches for steel bridges is thus necessary.

A manual [5] has been published for repairing and retrofitting fatigue cracks in steel bridges. Various methods are detailed therein, such as hole drilling, burr grinding, adding doublers/splice plates, *etc*. Some methods are commonly used, and some are seldom considered due to the retrofit cost, operability. A new method with low retrofit cost, and high efficiency remains necessary.

The impact crack-closure retrofit (ICR) treatment [6,7], is a new cold-working process where the cracked material is peened by high-speed impact, causing the crack surface to close and introducing compressive residual stresses. The cracked surface can be retrofitted or repaired within a few minutes [8]. Previous fatigue tests of ICR treated samples show substantial improvement in fatigue performance. For example, Yamada et al. [9,10] showed remarkable enhancement in fatigue strength of welded joints, and effective reduction in stress intensity factor (SIF). Ishikawa et al. [11] reported the extension of remaining fatigue life of cracked specimens subjected to bending. YuanZhou Zhiyuan et al. [12] made a comparing between drilling-hole method and ICR treatment indicating that ICR treatment was more efficacious.

The benefits of ICR treatment have been recognized, while the wide application to the field of *in situ* crack retrofitting is not considered yet due to its immaturity. Meanwhile, the reason for its retarding crack propagation and rehabilitation effects is still under discussion, which motivates this research.

In this study, fatigue tests were carried out on a steel plate with an artificial crack under cyclic bending. ICR treatment was conducted on the cracked surface, and the retarding effects on crack propagation were discussed.

2. Experimental details

2.1. Specimens

A 12 mm-thick steel plate specimen with a through-thickness artificial crack was used in this fatigue test, and it conformed to Chinese Standards [13] Q345qD. The size of the specimen is 600 mm long and 300 mm wide, and the artificial crack was manufactured by wire electrical discharge machining (WEDM). Fig. 1 shows the detailed dimensions of the test specimen. The chemical composition of the material (Q345qD) is given in the Table 1, in which the mechanical properties are also provided.

* Corresponding author at: College of Civil and Transportation Engineering, No. 1 Xikang Road, Nanjing, China.
E-mail address: bhji@hhu.edu.cn (J. Bohai).

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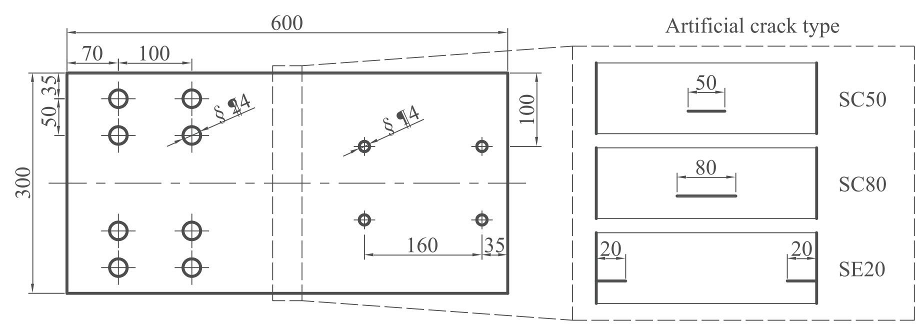


Fig. 1. Specimen dimensions.

Table 1
Mechanical properties and chemical composition of Q345qD.

Material	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Chemical composition (%)				
				C	Si	Mn	P	S
Q345qD	345	490	20	≤0.18	≤0.55	0.9–1.7	0.025	0.02

Three specimen types with different crack lengths and positions were considered, 50 mm long central crack (SC50), 80 mm long central crack (SC80), and 20 mm long edge crack (SE20), and all the crack width is 0.2 mm, due to the wire diameter. A total of 12 specimens were tested, and divided into six groups, considering different treatment cases: impact surface and range (see Fig. 2). All the specimens were numbered from SP1 to SP12 in the order of group numbers, respectively. Table 2 shows the detailed information about specimen classification.

2.2. Fatigue test procedure

Fatigue tests were carried out using a fatigue testing machine (see Fig. 3) that generated a plate bending type of loading by a vibrator, simulating a similar loading scheme in actual bridge operations [14]. The vibrator generates a centripetal force as a built-in unbalanced mass rotates, and the output stress range can be controlled by varying the rotational frequency. Two testing machines were used (M1 and M2), and the stress ratio was set to $R = -1$ in this fatigue test.

The specimens were first tested under cyclic loading to produce a specific length of real fatigue crack, because the manufactured cracks did not produce a plastic zone [15] at the crack tip, which might influence the subsequent crack propagation, causing a lower reliability of the test results. This procedure is called fatigue crack prefabrication (denoted by the first fatigue test, FFT) until the crack propagation length reached about 10 mm on each side. The total crack length consists of the artificial crack length and the fatigue crack length. The stress range was controlled to within 130 MPa–140 MPa. After the crack was prefabricated, the ICR treatment was applied to the cracked area. Then, the second fatigue test (SFT) with the same boundary conditions and loading frequency was carried out, until the specimen no longer bore load or the number of cycles reached about 6 million.

Table 2
Specimen classification.

Group number	Specimen type	Impact ranges	Impact surface	Number
G1	SC50	Fully coverage	Main Surf.	2
G2	SC50	Crack surface	Main Surf.	2
G3	SC50	Fully coverage	Main & Sub Surf.	2
G4	SC50	Crack tip	Main Surf.	2
G5	SC80	Fully coverage	Main Surf.	2
G6	SE20	Fully coverage	Main Surf.	2

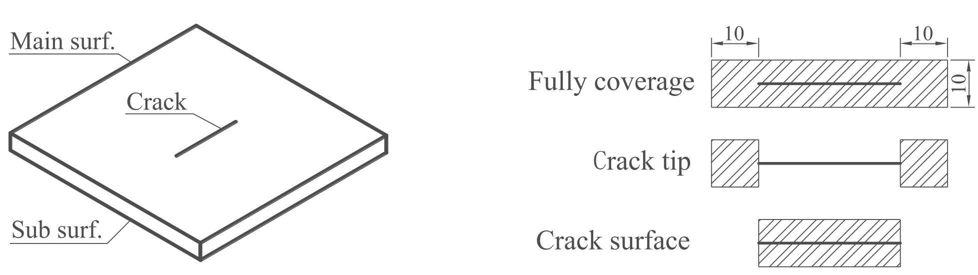
2.3. ICR treatment process

Devices being used for ICR treatment are a portable air compressor, an impact air tool, and a chisel (Fig. 4a). The chisel tip was burnished to a flat rectangular surface of 5 mm × 5 mm with its corner rounded. Other device parameters used during ICR treatment are listed in Table 3. The chisel was positioned 5 mm right above the crack surface for preparation, and the velocity of chisel horizontal movement was controlled to about 1 mm/s. Three impact steps were conducted to fully retrofit the crack surface (Fig. 4b).

An air-grinding tool was then used to deal with the irregularities on the surface after ICR treatment, removing burrs, and smoothing the surface. The same air compressor was used as the energy source for the air-grinding tool. Fig. 5 shows the different steps involved in this crack surface treatment.

2.4. Data collection

Fatigue stress was monitored by the strain gauges glued on the specimen surface (see Fig. 6) by using dynamic strain indicator with the type of uT7800 under a frequency of 512 Hz. The magnitude of the fatigue



(a) Impact surface (b) Impact range

Fig. 2. Different treatment cases.