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Fatigue performance test on inclined central cracked steel plates repaired with CFRP strand sheets

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ABSTRACT

An experimental study was conducted on central-cracked steel plates with different crack inclination angles that had been repaired with carbon fiber reinforced polymer (CFRP) strand sheets. Initial cracks with five different inclined angles (0–60°) were artificially induced from a central hole of steel plates. All the cracks had the same projection length, running perpendicular to the loading axis. Crack lengths, crack trajectories, failure modes and the effects of different repair configurations were investigated, and fatigue crack propagation lives were compared. A typical adhesive failure mode, oblique compression failure in the adhesive layer, was observed. A conclusion was drawn that fatigue life was directly determined by the projection length, while the projection length was calculated from the initial crack length and inclination angle. The average fatigue life extension ratio of specimens with single-sided repairs was 1.44; that of specimens with double-sided repairs was 3.03.

1. Introduction

Nowadays, fatigue cracks could be found in many steel structures subjected to cyclic loading and may result in catastrophic accidents. Indeed, infrastructures within developed countries currently face problems caused by fatigue cracks. In a survey of European railroad bridges [1], 66% of the bridges were over 50 years old, with 21% metallic bridges and 14% steel-concrete composite bridges. Another survey [2] showed that 80–90% of metallic bridge failures were related to fatigue damage. According to statistical results by the U.S. Federal Highway Administration in 2016 [3], there were a total of 180,540 metallic bridges in the United States that comprises 30% of all American bridges. Of those metallic bridges, 31,732 had structural defects, and fatigue damage was the primary cause of the defects. Fatigue improvement of these damaged steel structures is critical to their structural integrity [4]. These old railroad bridges will be subjected continually to fatigue load induced by heavy vehicles. Therefore, methods need to be developed to improve the fatigue performance of steel structures. Traditional repair techniques such as crack welding, stop holes, and steel plate attachment are either time-consuming or difficult to apply.

In recent years, CFRP repair of damaged steel structures has attracted a great deal of attention, due to the technical efficiency and ease of application. Extensive research has been conducted on this issue. With regard to fatigue performance improvement, several studies on CFRP repaired cracked steel plates have been carried out [5–8], in which different repair configurations, CFRP modulus and damage levels etc. were studied. Fatigue life may be extended by 1.18 – 3.08 times or 2.2 – 7.9 times by using single-sided or double-sided CFRP repair methods, respectively. Another study conducted by Yu et al. [9] exhibited a maximum fatigue life extension ratio of 29.4 of double-sided repair. It was the result of the very high initial damage level of 40% and the specific CFRP width, the same as plate width. Jiao et al. [10] investigated the fatigue behavior of cracked steel beams. Results showed that steel beams repaired with CFRP had a fatigue life 1.82–5.83 times that of crack-welded ones. Colombi et al. [11] also studied the fatigue behavior of cracked steel girders repaired with CFRP. Comparing to the control specimen, the repair may even have retarded fatigue crack propagation to some extent. Hosseini et al. [12,13] investigated fatigue performance of central cracked steel plates repaired with prestressed CFRP. Result showed that crack propagation was arrested under the specific prestress level. The same phenomenon was also observed by Ghafoori et al. [14,15] in cracked steel girders repaired with prestressed CFRP.

However, mode I fatigue cracks of steel plates have been the primary focus in such researches. Fatigue cracks sometimes propagate with an inclined angle rather than simply perpendicular to the loading axis [16], creating a mixed-mode I/II fatigue crack, which is very

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complex. There is no systematic research on mixed-mode I/II fatigue cracks in CFRP-repaired steel plates. In earlier aviation studies, scholars [17–21] investigated the fatigue performance of aluminum plates with mixed-mode I/II fatigue cracks repaired with CFRP. Results of those studies revealed that inclined cracks deflected in the early stage, i.e., they propagated under mixed-mode I/II, and then propagated almost perpendicular to the loading axis. The stress intensity factor (SIF) could be reduced by attaching composite patches. The fatigue performance of CFRP repaired steel plates with inclined central cracks of different inclination angles and damage levels was studied by Aljabar et al. [22,23]. Test result revealed that when the initial crack lengths are the same, smaller inclination angles to the loading axis lead to higher fatigue life. Mixed-mode I/II crack propagation in steel plates were also numerically simulated [24–26] with different types of specimens. Numerical results fitted well with the experiments. Nevertheless, both experimental and numerical studies are very limited. For CFRP laminates repaired specimens, debonding was often observed in FRP repaired steel members [27–29]. However, no debonding occurred in steel members repaired by the newly invented CFRP strand sheets [30,31]. Superior bonding behavior was observed between the CFRP strand sheet and the steel member. Furthermore, experimental study of Jiao et al. [32] revealed that the fatigue life improvement of defected steel elements repaired by CFRP strand sheets was comparable to that repaired with CFRP plates and high modulus CFRP sheets.

This paper, a continuing work of the authors [33,34], consists of a series of fatigue tests on CFRP-repaired steel plates with an inclined central crack. Two parameters were studied: (1) the crack inclination angle, with five angles (0°,15°,30°,45°, and 60° with respect to the axis perpendicular to the loading axis) introduced to simulate different initial damage conditions; (2) the CFRP repair configuration, with both single-sided and double-sided repair methods adopted to study the efficiency of different repair configurations. Unrepaired plates were set as control specimens.

2. Specimens and materials

2.1. Configuration of specimens

Specimens were designed according to the authors' previous work [33,34]. They were made of rectangular steel plates, with the repaired specimens patched with CFRP strand sheets bonded by epoxy adhesive. Hereinafter, the short axis is defined as the axis parallel to the short edge of the specimens, i.e. perpendicular to the loading direction. A total of 17 specimens was divided into three groups. Five specimens were repaired on only one side with one layer of CFRP strand sheet, which is sometimes the only way to repair damaged steel tubes that are inaccessible inside. Seven specimens, two of which were supplements, were repaired on both sides with one layer of CFRP strand sheet. The remaining five specimens were unrepaired. Detailed information on all 17 specimens is presented in Table 1, in which the symbol 'U' stands for the unrepaired specimen, the symbol 'SSF' refers to the single-sided repaired specimen, and 'DSF' stands for the double-sided repaired specimen.

The length, width, and thickness of the steel plates were 700 mm, 90 mm, and 8 mm, respectively. Steel plates had a center hole of 5 mm in diameter and two artificially introduced slots with a width of 0.18 mm and a circular front, whose angle to the short axis was variable, while the projection on the short axis was kept constant as 9 mm. Pre-cracking technique was not used because it is very hard to control the initial length. The CFRP strand sheets were 300 mm long and 30 mm wide, with a thickness of 0.429 mm. The configuration and geometry of the specimens are detailed in Fig. 1, in which θ represents the crack inclination angle. To simulate embedded defects with random inclination angles induced in the manufacturing process or resulted from the complex local stress, five angles (0°, 15°, 30°, 45°, and 60° with respect to the short axis) were introduced.

Table 1
Test matrix of specimens.

Specimen number	Crack inclination angle	Configuration	CFRP	Adhesive
U0	0°	Unrepaired	N/A	N/A
U15	15°			
U30	30°			
U45	45°			
U60	60°			
SSF0	0°	Single-sided repaired	FSS-HM-900	FB-E9S(ST)
SSF15	15°			
SSF30	30°			
SSF45	45°			
SSF60	60°			
DSF0	0°	Double-sided repaired	FSS-HM-900	FB-E9S(ST)
DSF15	15°			
DSF30	30°			
DSF30A	30°			
DSF45	45°			
DSF60	60°			
DSF60A	60°			

2.2. Material properties

Fig. 2 presents a close view of the CFRP strand sheet, which consists of bunches of individually hardened continuous fiber strands. Properties of all the materials are presented in Table 2. The steel plates applied in the experiment were Q345B, and their properties were tested according to Chinese Standard GB/T228–2010. The CFRP strand sheet, FSS-HM-900 from NIPPON STEEL & SUMIKIN MATERIALS®, was chosen for the experiment. The structural adhesive, FB-E9S(ST) from the same company, was used to bond the CFRP strand sheets. Since properties of these two materials were also tested by Hidekuma et al. [31] and Jiao et al. [32], and the tested data differed not much from that provided by the manufacturer, properties of these two materials were adopted from the data sheet provided by the manufacturer.

2.3. Preparation of specimens

Before patching CFRP strand sheets, the bond area of each steel plate was first sand-blasted to wipe out rust and oxide, roughening the surface. Then alcohol was used to remove grease and dust from the surface of both the steel plates and the CFRP strand sheets in order to strengthen the bond. The two components of the epoxy adhesive were mixed, then brushed evenly onto the steel plates and CFRP strand sheets. The CFRP strand sheets were then placed onto the designated area of the steel plates. Since Pastor et al. [35] concluded that the shear strength of adhesive plays an important role in the fatigue behavior of repaired specimens, the thickness of the adhesive was carefully controlled approximately as 0.4 mm via the method utilized by Wu et al. [8]. Two acrylic plates with a total thickness equal to the thickness of the adhesive and the CFRP strand sheet were set on both sides of the CFRP strand sheet. Another steel plate was then deposited on top to supplant extra adhesive and to prevent bubbles. Because the ambient temperature, 0–10 °C, was lower than that needed for the adhesive curing, 20–30 °C, all specimens were placed in the environmental cabinet for 7 days.

3. Test set-up

This experimental program was performed in the Durability Laboratory at Tongji University in Shanghai, China. An MTS322 fatigue testing machine was used to apply tension-tension fatigue loading with a frequency of 10 Hz and a stress ratio of 0.1. The fatigue testing machine and the arrangement of strain gauges, represented as ε, are presented in Fig. 3. Strain gauges 2, 3, 5, and 6 together with strain gauges 1 and 4 were set to monitor the strain of the steel plates on two surfaces