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Fatigue improvements of cracked rectangular hollow section steel beams strengthened with CFRP plates

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A B S T R A C T

Concerns over means to improve fatigue behavior of cracked rectangular hollow section (RHS) steel beams exist. This paper presents the details of strengthening schemes that was carried out using prestressed or high modulus carbon fiber reinforced polymer (CFRP) plates. A set of fatigue tests were conducted and results indicated that prestressed CFRP technique could increase fatigue crack propagation life 35.57 times longer than that of unrepaired one. The results also indicated that high modulus CFRP is effective at increasing fatigue life. Following crack propagation lives were calculated based on finite element models and close agreement with test results were observed. Thereafter, a parametric study was conducted considering the influence of various parameters such as the CFRP prestressing level, plate width and modulus on the fatigue life of the strengthened specimens. The findings of this paper can be employed to formulate design guidance for RHS beams under fatigue loading.

1. Introduction

Hollow section steel members have been adopted as structural members in bridges, civil buildings, offshore structures and even cranes. These members are often subjected to bending under external actions during service, and they may have structural deficiencies due to fabrication or harsh environments [1–4]. Fatigue cracking is a predominant problem for structures subject to repeated loading [3,5]. Thus, a critical need exists for repair techniques that allow convenient rehabilitation. However, traditional welding or bolting methods involve additional heavy plates and other applications that lead to fatigue sensitive defects [6,7]. In recent decades, carbon fiber reinforced polymer (CFRP) materials have been adopted as a popular repairing material for steel members [8–11]. Previous investigations showed the fatigue lives of repaired specimens can be greatly extended by non-prestressed CFRP repair methods [1,12–16] and even increased 21.5 times over that of control specimens using prestressed CFRP repair method [12]. Extensive research has focused on prestressed CFRP patched elements subjected to uniaxial loading [13,15,17,18].

A great deal of attention has also been paid to structural elements subjected to bending moments. Most of them have been conducted on the "I" section steel beams [16,19–21] and circular hollow section (CHS) beams [4,8,22] strengthened with CFRP materials. Linghoff et al. [23,24] conducted four-point bending tests on steel beams with I cross-sections strengthened with various configurations of CFRP laminates. Increased moment capacity was found. Finite element analyses of steel beams were also performed as a parametric study to capture the behavior of the strengthened specimens. Experimental research has also shown the effectiveness of CFRP rehabilitation on damaged CHS members under three-point bending [22]. Fatigue performance of the CFRP strengthening system has been reported. Colombi and Fava [25] carried out fatigue tests on nine cracked steel beams, each with an I cross section strengthened with a CFRP plate. Fatigue crack growth was retarded and fatigue life was prolonged. Jiao et al. [26] investigated eight notched steel beams strengthened with strand CFRP sheets. The specimens were subjected to fatigue loadings and fatigue life enhancement was achieved. CFRP strengthening was confirmed as an ideal way to rehabilitate cracked steel beams after comparing fatigue performance with traditional strengthening methods [27]. In the aforementioned studies, artificial slot was employed to simulate the initial damage degree instead of welded details. The purpose is to eliminate scatter of fatigue results due to welding that can introduce residual stress, kinds of imperfections such as pores, blowholes, under cuts and heat affected zone.

The prestressing technique is often used to strengthen steel beams by CFRP plates to exploit its high strength. Walbridge et al. [28] carried out fatigue tests on strengthened I-beams with welded cover plates. The results indicated that a significant fatigue life enhancement can be achieved by applying prestressed CFRP strips to the cover plates. Numerical analysis with a fracture mechanics model were performed to predict fatigue life with reasonable results. Due to the complexity of weld details, artificial notched steel elements were introduced.

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Ghafoori et al. [16] investigated notched steel I-beams strengthened with prestressed CFRP and developed a theoretical method to calculate the prestressing levels in CFRP by controlling the stress intensity factor at the crack tip. The prestressed CFRPs were further employed to increase the buckling strength of steel I-beams with experimental and numerical approaches [29]. In regards to the strengthening of a rectangular hollow section (RHS) structural members, research focused on monotonic loadings [30,31], but limited research dealt with fatigue problems [32,33]. Field application with prestressed CFRP laminates were reported by Koller et al. [33]. A cracked steel pendulum was monitored and fatigue cracks ceased to propagate for nine years. In summary, the prestressed CFRP strengthening method is effective for steel members with open and closed sections.

Previous research indicates the fatigue performance improvement with hollow section steel members. However, to further explore the application of prestressed CFRP in this area, systematic experimental and numerical efforts are required. The aim of this paper is to examine and compare the fatigue life improvements of CFRP-strengthened RHS steel beams with different CFRP moduli and prestressing levels with un-strengthened ones. Firstly, six strengthened specimens were tested under four-point fatigue bending. The results were compared to that of the un-strengthened control specimens. Subsequently, a numerical simulation technique for studying the cracking behavior of RHS steel beams subjected to fatigue loading was developed and validated against experimental testing data. A study was then carried out on the effects of several strengthening related parameters as they relate to the response of the cracked beams using validated numerical models.

2. Experimental investigation of fatigue crack propagation life

2.1. Experimental program

The specimens were fabricated by patching CFRP plates to the bottom notched steel beams. Fig. 1 shows the basic geometry of the strengthened cracked RHS steel beams considered in this study. They were 700 mm long with an RHS cross section, which measured 100 mm × 50 mm × 6 mm. Initial damage was simulated by a notch on the bottom of the steel beam. It was cut by wire electrical discharge machining. The width of the notch was 0.18 mm and the crack depths were 10 mm or 30 mm. The lower surface was sandblasted and cleaned with acetone before applying adhesive and patching with a CFRP plate. Two types of CFRP plates with normal or high modulus were used and they had dimensions of 500 mm long and 20 mm wide. As for the prestressed CFRP plate, they were tensioned with a hydraulic jack.

Four series of tests, with a total of eight specimens, involving different combinations of CFRP types, prestressing levels and initial damage levels were considered. The test matrix are presented in Table 1. Series A consists of two un-retrofitted beams with a 10 mm or 30 mm initial crack as the control ones. Series B and C includes specimens repaired with normal modulus CFRP plates that are designated by NC followed by either N or P, indicating non-prestressed or prestressed CFRP plates, respectively. Series D is two specimens repaired with non-prestressed CFRP plates of high modulus. HC refers to the used type of CFRP plate with high Young's modulus.

Table 1
Test matrix.

Series	No.	Initial crack depth (mm)	CFRP prestressing level (%)	CFRP modulus (× 10^5 MPa)	Loading ranges 2 *P* (kN)	Fatigue life (Cycles)
A	RHS-1	10	/	/	8–80	31,168
	RHS-2	30	/	/	5.5–55	13,803
B	NC-N-1	10	0	1.91	8–80	104,362
	NC-N-2	30	0	1.91	5.5–55	64,599
C	NC-P-1	10	22	1.91	8–80	232,055
	NC-P-2	30	22	1.91	5.5–55	491,014
D	HC-N-1	10	0	4.60	8–80	112,173
	HC-N-2	30	0	4.60	5.5–55	194,579

Table 2
Material properties of steel, CFRP and adhesive.

Property	Steel	CFRP-1	CFRP-2	Adhesive
f_y (MPa)	298	–	–	–
f_u(MPa)	368	3089	1500	28.6
E_1 (GPa)	190	191	460	1.9
E_2 (GPa)	–	10.8	18.4	–
ν_{12}	0.30	0.27	0.30	0.36
G_{12} (GPa)	–	6.0	7.7	–
t (mm)	6.00	1.40	1.55	0.40

Tensile coupon tests were performed for steel tubes and results showed in Table 2. All the steel tubes were fabricated from one batch of material. The material properties of the steel, CFRP plates and adhesive are given in Table 2.

2.2. Specimen preparation

The specimen preparation consists of surface grinding, applying adhesives and patching CFRP plates. A major challenge of exploiting the high tensile strength of CFRP is prestressing the CFRP plate during specimen preparation. In this research, an instrumentation was employed to fulfill the prestressing process (Fig. 2). A bare specimen was positioned with the prestressing instrumentation. Thereafter, a CFRP plate was bolted at one end with the specimen using mechanical anchorage systems. The other end was clamped by steel plates that lined to the far end steel plate trough steel bars. Subsequently, a hydraulic jack was used to pull the steel bars. Strain gauges were mounted on CFRP plate surface to monitor the prestressing level until designed values. The anchorage systems was also used to fix both CFRP plate ends to delay or prevent debonding between CFRP plate and steel beam for non-prestressed CFRP repaired specimens. Thereafter, specimens were subjected to fatigue loading, and propagation phenomena were recorded.

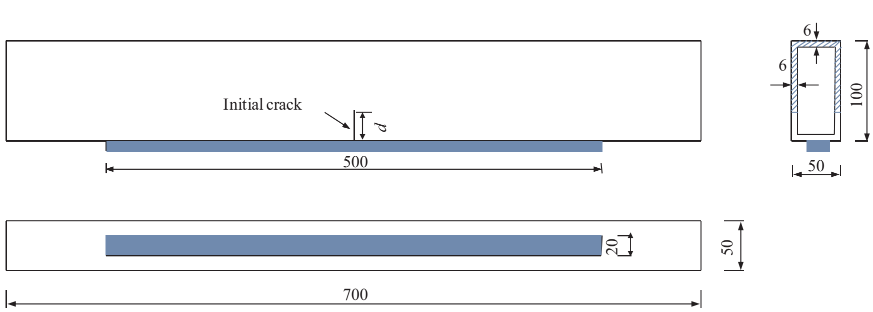

Fig. 1. Geometry configurations (unit: mm).