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J-integral approach for main crack propagation of RC beams strengthened with prestressed CFRP under cyclic bending load

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ABSTRACT

Compared to the passive bonding strengthening technique using carbon fiber reinforced polymer (CFRP) for reinforced concrete (RC) structures, an active strengthening technique with prestressed FRP for reinforcing RC bridge structures with crack-like defects can make the stress distribution more reasonable, and can inhibit crack propagation. In this study, experimental and numerical methods were applied to investigate the fatigue crack propagation behavior of RC beams strengthened with prestressed carbon fiber laminate (CFL). Fatigue crack propagation tests were carried out to obtain the crack propagation rate on RC beams strengthened with CFL, which had different prestressing levels (0%, 15%, and 22%). The digital image correlation (DIC) method was used to capture the fatigue crack pattern. The finite element method was applied to calculate the J-integral of the main crack on RC beams strengthened with prestressed CFL. For accurate description of the fatigue crack propagation and fatigue life prediction, fatigue crack propagation tests were conducted. Based on a theoretical derivation, a modified version of Paris' law was proposed. Compared to RC beams strengthened with non-prestressed CFL, the main crack propagation rates on RC beams strengthened with prestressed CFL having prestressing levels of 15% and 22% were decreased by 38.6% and 43.0%, respectively. Higher prestressing levels contribute to a greater resistance to crack propagation.

1. Introduction

The application of bonded carbon fiber-reinforced polymer (CFRP) to the surfaces of concrete members provides an efficient, lightweight, and non-corrosive alternative to other repair methods such as bonding steel plate. However, the non-prestressed CFRP strengthening technique (passive reinforcement technique) has attracted the attention of researchers and engineers for its insufficient use of the strength of CFRP. To overcome the limitations of the passive reinforcement technique, researchers have developed a new active reinforcement technique with CFRP, which is referred to as the prestressed CFRP strengthening technique.

The existing research results show that the prestressed CFRP strengthening technique has the following advantages: it significantly increases the loading level of the FRP, increases the cracking load of the strengthened members, improves the stress distribution of the members, closes existing cracks, and increases the fatigue life and durability of the strengthened structures.

At present, with the development of the strengthening technique with prestressed CFRP, the fatigue performance and durability of reinforced concrete (RC) structures strengthened with prestressed CFRP has been receiving increasing research attention. Some researchers [1,2] have conducted experimental studies on the fatigue behavior of concrete T-beams strengthened with prestressed

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Nomenclature

ΔJ	amplitude of the J-integral
G_f	critical fracture energy
$P_{\max}$	peak load
P_u	ultimate load bearing capacity
a	crack length
N	number of loading cycles
N_f	fatigue life
D	damage of CFL–concrete interface
C	material parameter of Paris' Law based on the J-integral
m	material parameter of Paris' Law based on the J-integral
f_{cu}	uniaxial compressive strength of concrete
f_t	uniaxial tensile strength of concrete
$S_{\max}$	maximum stress
$S_{\min}$	minimum stress
τ_{max}	maximum shear stress
E_c	initial elastic modulus of concrete
E_{cf}	elastic modulus of CFL
ν_c	Poisson's ratio of concrete
δ_0	slip corresponding to τ_{max}
δ_f	maximum slip
R	stress ratio
d_c	damage parameter of concrete
ΔT	temperature exchange value
σ_{pe}	prestress in CFL
α	thermal coefficient of linear expansion of CFL

CFRP. The research results obtained by EI-Hacha et al. [3] showed that prestressed CFRP sheets could greatly increase the fatigue life of specimens, and the anchorage condition also had a significant influence. Xie et al. [4] conducted experiments to investigate the fatigue damage behavior of RC beams strengthened with prestressed CFRP. The results showed that the prestressed CFRP could further reduce the stresses on the steel bar and the fatigue damage, and increased the fatigue life of RC beams. An accumulative damage model based on the flexural stiffness was also established. Huang and Fadi [5,6] proposed models for predicting the fatigue life of RC beams strengthened with prestressed CFRP under bending loads.

To establish the fatigue failure mechanism for RC members strengthened with prestressed CFRP, investigation of the fatigue crack propagation behavior of strengthened RC members is very important. To describe the fatigue crack propagation behavior of non-prestressed CFRP strengthened RC members, Paris' law has typically been used. Previous research by this group [5] on the strengthening of RC beams showed that Paris' law is effective. However, if Paris' law is to be applied to describe the fatigue crack propagation behavior in RC members strengthened with prestressed CFRP, the following two key problems first need to be addressed: (1) accurate measurement of crack parameters such as the crack increment, *da*, in fatigue crack propagation experiments; and (2) precise calculation of the stress intensity factor (SIF) or J-integral of the cracks.

For accurate calculation of the crack propagation rate, da/dN, the fatigue crack size, a, should be accurately measured during fatigue crack propagation experiments. When a fatigue crack propagates in concrete, accurate measurement of the crack propagation using the traditional methods is difficult. In recent years, some researchers [7,8] have shown that the digital image correlation (DIC) method is a powerful tool for monitoring cracks. Mahal [7] used the DIC technique to investigate the fatigue behavior of RC beams strengthened with externally bonded CFRP; the crack width and deflection of the beam were obtained. Verbruggen [8] applied the DIC technique to monitor the cracking and failure behavior of RC beams strengthened with CFRP under a four-point bending static load. Although DIC has most often been applied to investigate the cracking behavior of RC structures under static load, it is also a powerful method for studying the fatigue crack propagation behavior of RC structures, even though the related research is still limited. Therefore, the DIC method was applied to investigate the fatigue crack propagation behavior of RC beams strengthened with prestressed CFRP in this study.

To calculate the SIF of the cracks in RC beams strengthened with CFRP, this research group [9,10] has previously applied theoretical derivation and the finite element method, and the studies have been successful. However, considering the quasi-brittle and nonlinear characteristics of concrete, SIF has a limited ability to describe crack initiation and propagation in concrete. The J-integral is more appropriate for describing crack propagation behavior in concrete. Therefore, the J-integral calculation method for the fatigue cracks in RC beams strengthened with non-prestressed carbon fiber laminate (CFL) has been reported [10].

Based on the above discussion, this paper is divided into two sections. First, fatigue crack propagation tests were carried out for RC beams strengthened with prestressed CFL to obtain the crack propagation rate, *da/dN*, and the DIC method was applied to monitor the fatigue crack propagation behavior during the experiments. Next, a finite element model of the RC beam strengthened with

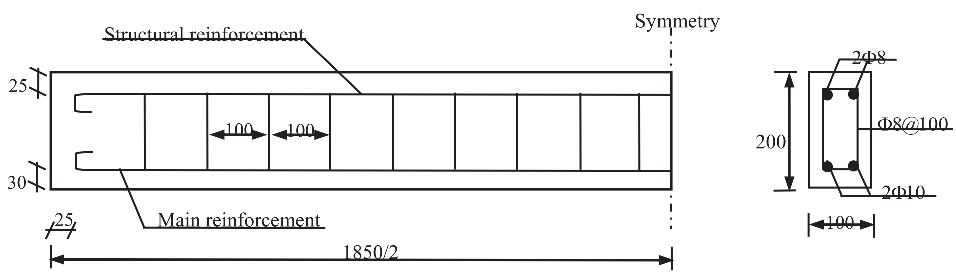

Fig. 1. Steel bars used in the RC beam.