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Fatigue and durability behavior of RC beams strengthened with CFRP under hot-wet environment

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HIGHLIGHTS

- A hot-wet environment and fatigue load coupling experimental method was proposed.
- Hot-wet environment and load coupling action advisedly affects the fatigue lives.
- Equations of hot-wet environment and fatigue load coupling action were proposed.

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ABSTRACT

Real service environment has a significant influence on fatigue and durability behavior of the members since the main reinforced concrete (RC) structural members of bridges are served under vehicle loads and environment coupling action. However, environment and loads were considered separately (uncoupling) in traditional durability experiments. This was different from the real service conditions of the main structural members of bridge. In this paper, three groups of RC beams strengthened with carbon fiber laminate (CFL) were tested under three point bending fatigue loads with uncoupled hot-wet environment (Group A: 50 °C, 95% R.H) and coupled environments (Group B: 50 °C, 95% R.H; Group C: 50 °C, 85% R.H) to discover the effect mechanism on fatigue and durability behavior of RC members strengthened with carbon fiber reinforced polymer (CFRP) under environment and fatigue load coupling and uncoupling action. Moreover, the fatigue test results in atmospheric condition at room temperature (23 °C, 78% R.H) in earlier stage were compared and analyzed. The research results have shown that the hot-wet environmental fatigue equation of strengthened beams that being proposed was effective and feasible. Comparing with traditional environment fatigue experiment (uncoupled), fatigue limit of strengthened beams under coupling action was relatively lower (decreased 20%) in high temperature and humidity environment (50 °C, 95% R.H). The higher load level was, the greater the fatigue life decreased.

1. Introduction

With the extensive use of fiber reinforced polymer (FRP) strengthening technology in civil engineering around the world, durability problem of reinforced concrete (RC) structure strengthened with FRP was brought into forefront [1–6]. At present, durability study of FRP strengthened RC structure is mainly based on experimental research refers to aging test procedures of related materials, which is the traditional experimental method of environment and loads uncoupling action [7,8]. In the above method, pretreatment of specimens was carried out in a single or multiple environments, static or fatigue tests were then carried out inside the lab at room temperature.

In major experiments, FRP specimens, FRP-concrete interface specimens or FRP strengthened RC beam specimens were exposed in a single environment first and static or fatigue tests were then carried out to discuss the environmental effects [9–11]. For example, Francesco Micelli [9] considered temperature and humidity seasonal variation. In the test, durability test condition of temperature and humidity cycling was set for FRP material, which

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simulated raining night and raining day in different seasons. Gheorghiu C [11] carried out static and fatigue experiment research to discuss durability of carbon fiber reinforced polymer (CFRP) strengthened RC beams, which had been exposed to wet-dry cycling or long term immersed in natural water. It has been proved that environment pretreatment influenced the shear failure mechanism of interface between CFRP and concrete in the strengthened RC beam. However, whether the single environment factor or multi environment factors in pretreatment are simulated in these tests, the majority of the durability test loads were static and some tests under fatigue loads were less adopted. Moreover, environment and loads were considered separately in above traditional environmental fatigue and/or durability experiment (uncoupling), which was hard to discover environment and load coupling action or coupling mechanism and was different from the real service conditions of main bridge structural members.

To study coupling effect of environment and load combination, Zachary B. Haber [12] discussed flexural behavior of CFRP strengthened beams under coupling effect of thermal cycling and loads. Jiawei Shi [13] analyzed durability of interface between basalt fiber reinforced polymer and concrete under coupling effect of freezing and thawing cycling and dead loads. Huitao Ren [14] studied durability of CFRP sheets under coupling effect of freezing and thawing cycling and dead loads. This research team systematically studied environmental fatigue and/or durability behavior of RC beams strengthened with CFRP under coupling effects of temperature and (random) fatigue loads [15–17]. However, for restriction of experimental conditions and test equipments, single environment factor was considered to be coupled with fatigue loads and real service environment of bridge structures had not been simulated, moreover, influence mechanism of environmental fatigue/durability behavior under uncoupling and coupling effects of same environment condition had not been discussed.

To carry out environmental fatigue/durability experiment of RC specimens strengthened with FRP under time varying hot-wet environment and vehicle load coupling action, the environmental fatigue/durability experiment method of RC members strengthened with FRP under hot-wet environment was proposed by this research team. The environmental fatigue/durability testing system for bridge structural members under time varying hot-wet environment and vehicle load coupling action was developed [18,19], which established good conditions for the study of this paper. Research objects of this paper are the RC bridge components strengthened with CFRP serviced in subtropical areas. Fatigue and durability behavior of RC members strengthened with CFRP under environment and loads coupling and uncoupling action was discussed to discover the effect mechanism on fatigue and durability behavior of the strengthened members with the above two experimental methods .

2. Environment fatigue equation of strengthened RC members

In our previous research [17], the major influences of environment temperature considered in effect mechanism on fatigue behavior of RC members strengthened with FRP were: producing temperature stresses, reducing shear performance of FRP-concrete interface and deterioration working condition of steel bars etc. For hot-wet environment discussed in this paper in addition to the influence of temperature, humidity also effect fatigue/endurance performance of FRP strengthening RC components as following: (1) humidity stress was produced in the strengthened member without any external loads when humidity increased, and the fatigue behavior of the members was affected, because of that there was different moisture absorption rate of main materials of strengthened members which were FRP, steel bars and concrete; (2) fatigue lives of strengthened members were related to the behavior of interface between FRP and concrete (including permeable layer) shown in previous research [16], because the interface (including permeable layer) was composed of concrete and adhesive of which behavior was sensitive to humidity. High humidity decreased shear strength of adhesive and even made the adhesive lose strength; (3) When humidity increased, shear strength of the interface decreased, and more loads would be carried by the main steel bar in strengthened members, which caused earlier damage of the main steel bars; Damages of main steel bar increased load distribution to the interface in return, which accelerated the fatigue damage of the interface. Finally caused accelerating debonding failure of the interface and the decrease of fatigue life of the strengthened members; (4) When the strengthened members were exposed in high humidity environment for long time, steel bars were corroded, moreover, the higher humidity was, the faster the corrosion took place, which caused significant decrease of the fatigue performance of the strengthened RC members.

For hot-wet environment and fatigue load coupling effects, when the RC members strengthened with FRP were cracked, steel bar corrosion caused by humidity was more obviously, moreover, theoretical analysis indicated that, in high temperature and high humidity environment, coupling effects of temperature and humidity accelerated the decrease of fatigue performance of RC members strengthened with FRP.

For reasons given above, when hot-wet environment varied, external force, temperature and humidity coupling effects should be considered into fatigue life calculating formula of RC members strengthened with FRP. Therefore, on the basis of preliminary work [17], considering the effect of humidity on fatigue lives of the members again, fatigue life equation of RC members strengthened with FRP under hot-wet environment and cycling loads coupling action effects cloud be assumed as:

$$S^{m(T,H)}N = C \tag{1}$$

where, S represents cycling stress/load, $m(T,H)$ stands for material performance function related to temperature T and humidity H, N is load cycling count, also known as fatigue lives of strengthened members, C indicates constant.

Take logarithm on both sides of Eq. (1) and convert into series forms, then,

$$S = \sum_{n=0}^{\infty} \frac{\left\{\frac{A}{m(T,H)}[log10(C) - log10(N)]\right\}^n}{n} \tag{2}$$

Expand Eq. (2), retain the constant term and linear term of the series, then,

$$S \approx 1 + \frac{A}{m(T,H)}[\log 10(C) - \log 10(N)] \tag{3}$$

For there-point bending rectangular strengthened beams under concentrated load P, Eq. (3) was written as:

$$P = \frac{2bh^2}{3L}\{1 + \frac{A}{m(T,H)}[\log 10(C) - \log 10(N)]\} \tag{4}$$

where, b, h, L is respectively the width, height and span (distance between two supporting points) of strengthened beam, A is constant.

The equation of material performance function, $m(T,H)$, in hot-wet environment was assumed as:

$$m(T,H) = \frac{A}{A_1 + A_2 e^{A_4 T} + A_3 e^{A_5 H}} \tag{5}$$