Construction and Building Materials 166 (2018) 345–355

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Crack growth modeling of tension lap spliced reinforced concrete beams strengthened with fibre reinforced polymer wrapping under fatigue loading

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HIGHLIGHTS

- A crack growth model has been developed to strengthened and unstrengthen RC beam with lap splice under fatigue loading.
- A linear relationship found between the constant α from the crack growth parameter and the monotonic average shear stress, as the average shear stress increases the value of the α decreases.
- The average shear stress of the monotonic test results fell close to the intercept of the shear stress – fatigue life curve on logarithmic – logarithmic scales at one cycle.
- There is a good agreement between the calculated number of cycles and the actual fatigue data for all tested beam.

ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form 10 January 2018
Accepted 24 January 2018
Available online 22 February 2018

Keywords:
Lap splice
Bond behavior
FRP strengthening
Crack growth
Fatigue loading

ABSTRACT

This study was aimed at increasing our understanding of the behavior of the bond between a steel bar and the concrete along a lap splice region for structures subjected to cyclic loading. An additional aim of the study was to investigate the effect of fatigue loading on the bond between concrete and steel, and the ability of the new high and low modulus fiber-reinforced polymer (FRP) sheets to enhance the fatigue performance of a tension lap splice. A crack growth model was developed to calculate the fatigue life of the bond specimens. The model results were compared with the experimental outcomes of fifty-three beams tested under fatigue and monotonic loading. There is a good agreement between the calculated number of cycles and the actual fatigue life data for all different wrapping conditions and different concrete cover thicknesses. The difference between the calculated and measured fatigue strength curves did not exceed seven percent.

1. Introduction

A lap splice is a common connection method used in reinforced concrete structures to transfer tensile forces from one steel rebar to the other because of the efficiency, simplicity and low cost compared to the other connections methods. A drawback of using short length of lap splice is the bond strength issue especially under fatigue loading. Fatigue loading deteriorates the bond between the steel and concrete at the lap splice region resulting in a decreased load carrying capacity. Many reinforced concrete members containing lap splice are subjected to fatigue loading and require strengthening to increase their service lives. Several strengthening methods have been used to increase the bond strength such as increasing the concrete cover of the member, replacing the old concrete cover with a new high strength concrete, adding a transverse reinforcement either internal as stirrups or external as a steel plate and adding a wrapping of external FRP sheet. These strengthening methods have limitations. Increasing the concrete cover of the reinforced concrete member, replacing the old concrete cover with new high strength concrete and adding transverse reinforcement may require more space during construction than is available. A drawback of using steel plate is the problem of steel corrosion. Moreover, it increases the dead load on the reinforced concrete structure [1–4]. On the contrary, the FRP sheet wraps do not suffer from the above drawbacks. They are compact and light due to their high strength to weight ratios and do not corrode. Also

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https://doi.org/10.1016/j.conbuildmat.2018.01.136
0950-0618/

they have high fatigue strengths and are easily bonded to the external surface of a reinforced concrete member [5].

The repair of reinforced concrete beams using FRP sheets has become popular as a new technique for strengthening lap spliced beams. A review of the literature revealed that the majority of the research on strengthening the bond of the reinforced concrete beams containing lap splices was performed under monotonic loading (Garcia et al. [6]; Shihata [7]; Hamad et al. [8–10]; Soudki and Sherwood [11,12]) and some research studied the effect of the FRP wrapping around columns under seismic loading (Bournas and Triantafillou [13] and Bousias et al. [14]). To the authors' knowledge, no one has investigated the effect of FRP sheet wrapping on the bond strength of reinforced concrete beams containing lap splices under fatigue loading. The absence of experimental data on the strengthening of reinforced concrete beams containing lap splices reinforced with FRP sheets under fatigue loading has delayed the development of a model able to predict the fatigue performance of the bond between steel and concrete.

Alyousef et al. [15–18] investigated the effect of FRP sheet wrapping on the bond strength of reinforced concrete beams with lap splices under monotonic and fatigue loading. A total of fifty-three beams were constructed and tested under monotonic and fatigue loading were divided into three groups that were Group 1 (20 mm concrete cover), Group 2 (30 mm concrete cover) and Group 3 (50 mm concrete cover). The splice length was 300 mm to maintain the minimum length allowed by the ACI and the Canadian standards, and to ensure a bond failure would occur before the steel yielded. Three beams from each group were tested under monotonic loading while the rest of the beams were tested under fatigue loading. The beams cross section and reinforcing details were the same for all beams. The beam was 2200 mm long, 250 mm wide and 350 mm in height. Two symmetric applied loads provided a constant moment region at the mid span of the beam. The span between two supports was 1800 mm divided into three equal length regions, two shear span regions and a constant moment region containing the lap splice. Each beam was reinforced with two 20 M steel rebars spliced at the mid span. The lap splice was placed in the constant moment region to study the effect of the FRP wrapping on the bond strength where the nominal stress is uniform and there is no shear stress. Two 10 M deformed bars were used in the compression zone outside the constant moment region. This test beam was designed without internal transverse reinforcing stirrups within the constant moment region of the splice to allow a separation of the effect of confinement by the U-shaped FRP sheets on the bond strength from the effect of confinement by stirrups. Two types of FRP wrapping sheets were used in this study. The GFRP sheet used was 430G and the CFRP sheet used was 900C. The weights of the GFRP sheet and the CFRP sheet were 430 g/m^2 and 900 g/m^2, respectively. The CFRP wrapping sheets were used with two types of epoxies that were 300 and 330. The concrete surface was primed with epoxy 330 and the CFRP sheets were saturated with epoxy 300 and then the CFRP sheets were placed on the concrete surface. However, the GFRP wrapping sheets used only epoxy 330. The average concrete compressive strength was 42 MPa, 33 MPa and 35 MPa at the 28-day specified strength based on standard CSA A23.3-2004 [19] for Group 1, Group 2 and Group 3, respectively. A minimum applied load of 10% of the ultimate monotonic failure load was used for all fatigue tests. This minimum load was applied to represent the dead load on a structural member and to prevent beam movement at the minimum load. The maximum load was varied to obtain fatigue lives between 1000 and 1,000,000 cycles. After each beam was tested, the maximum applied load was increased or decreased for the following beam so that its estimated fatigue life lay between 1000 and 1,000,000 cycles. After more than two test results were obtained, a linear log-log curve fitted to the previous data was used to choose subsequent load levels. A fatigue life of 1,000,000 cycles was taken as a runout fatigue life. Beams that had reached a million cycles without failure were tested again at a higher load level.

The main conclusions of the test results from the previous papers Alyousef et al. [15–18] were; as the thickness of the concrete cover increased, the bond strength increased under both monotonic and fatigue loading and as the fiber strengthening confinement increased, the bond strength increased under both monotonic and fatigue loading compared to the unwrapped beams. Also, the relationship between the length of the splitting cracks and the monotonic load was linear as the longitudinal splitting cracks increased in length from both ends of the lap splice as the load increased as shown in Fig. 1. The figure shows measurements of crack length from one end of the splice versus load in the monotonic test of an unwrapped beam.

2. Failure analysis and modeling

2.1. Mode of failure

A single mode of bond failure was observed for all beams tested under fatigue loading namely: splitting bond failure. This bond failure was characterized by longitudinal splitting cracks that resulted in a partial debonding of the reinforcing steel bar from the surrounding concrete in the lap splice region. For the unwrapped beams, longitudinal splitting cracks occurred on the bottom face at both ends of the lap splice at the beginning of the fatigue tests as shown in Fig. 2. As the number of cycles increased, the splitting cracks propagated at both ends of the lap splice. The cracks grew in length and width until failure occurred. The rate of growth of the splitting cracks increased as the applied load range increased.

It was noticed that, in the lap splice beam confined with stirrups, splitting cracks initiated at the beginning of the fatigue test from both ends of the lap splice and propagated toward the other end as load cycling continued [20–22]. For the lap splice beams confined with FRP sheets, the presence of the FRP sheets prevented the visual monitoring of the splitting cracks.

2.2. Shear stress distribution and crack growth model (Wahab et al. [23])

Wahab et al. [23,24] studied the shear stress distribution and crack growth in the bond of near surface mounted prestressed FRP bars. It was found that, during a fatigue test, the bond length can be divided into two regions: a fully bonded region and a

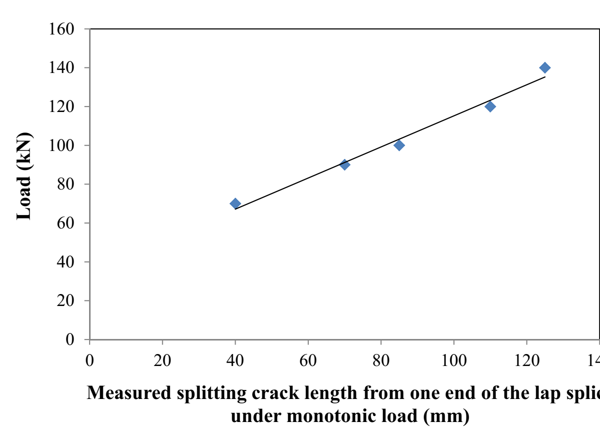

Fig. 1. Increase in splitting crack length with monotonic load for the unwrapped beam with 20 mm concrete cover.