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Performance of CFRP Strengthened Reinforced Concrete (RC) Beams in the presence of delaminations and Lap Splices under Fatigue Loading

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ABSTRACT: Externally bonded Carbon Fiber Reinforced Polymer (CFRP) sheets have been successfully applied to reinforced concrete (RC) beams and other structural elements to increase the load carrying capacity of such elements. The focus of this study is the combined effect of wet-dry environmental exposure and fatigue on the performance of CFRP strengthened RC beam system with installation defects in the form of induced delaminations. The test program consists of four CFRP sheet strengthened reinforced concrete beams; three with induced delaminations between the concrete substrate and CFRP sheet and one without delaminations to serve as a reference specimen. Mid-span deflection, crack widths, strains in the rebar and in the CFRP sheet as well as delamination size were measured during the course of fatigue loading. The effect of delamination on the performance of CFRP strengthened reinforced concrete beams, under fatigue and wet-dry cycles, is discussed and recommendations regarding the size of the tolerable delamination are made. The test results indicated that largest delamination size considered in this study did not affect the fatigue performance of CFRP strengthened RC structures; hence the beams with smaller size delaminations were not used to study the effect of delaminations but used to investigate the effectiveness of the repair techniques such as lap splicing the delamination region with new FRP sheets.

1. INTRODUCTION

Structural elements such as beams, slabs and columns may require strengthening during their service life period. The need for strengthening may arise due to one or a combination of several factors including construction or design defects, increased load carrying demands, change in use of structure, seismic upgrade, or meeting new code requirements. Studies have shown that Fiber Reinforced Polymer (FRP) composites, in the form of sheets, have emerged as a viable, cost-effective alternative to steel plates or other techniques in strengthening RC members (Saadatmanesh 1991, Meier 1993). The principal advantages of FRP sheets over steel plates include high strength-to-weight ratio, corrosion resistance and flexibility in its use. Another significant advantage of this repair technique is that overall repair cost in terms of labor, material and equipment is low and can offset the high material cost. However, the long-term durability and performance of FRP sheet strengthened RC members is a concern in civil engineering community. In North America and some European countries highway bridges are subjected to a variety of harsh conditions such as de-icing salts, moisture and exposure to a wide range of temperatures. It is feared that these exposures may lower the performance of the composite materials and/or their bond to the RC structural elements and hence affect the performance of such strengthened structural elements.

This study examines the fatigue performance of CFRP strengthened RC beams in the presence of delaminations, that occur due to installation defects, in combination with wet-dry cycles. The requirements of lap splice length for CFRP sheet under fatigue loading are also investigated.

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2. FATIGUE AND WET-DRY CYCLES IN HIGHWAY BRIDGES

Highway bridges are designed to resist fatigue loading. Fatigue can be defined as the process of progressive and irreversible deterioration in a material subjected to repetitive stresses. Fatigue is expressed by a parameter called "fatigue life" which represents the number of cycles needed to fail the material under a given repetitive load. The reasons for considering the effect of fatigue in the design of reinforced concrete structures are very well documented in the first and subsequent reports of ACI Committee 215 (ACI Committee 215).

The various structural elements in an RC highway bridge are exposed to wet-dry cycles resulting from rain and variable humidity conditions. While wet-dry cycles have little documented effect on RC structural elements, they may affect the bond between the composite materials and RC structural elements. Wet-dry cycles simulate the in-situ conditions of application of FRP sheets in highway bridges such as runoff water due to a poor deck joint, deficient drainage, traffic splashes or variable humidity conditions (Yves et al. 1998).

Delaminations usually occur when FRP sheets are attached to RC structural elements by wet lay-up procedure. The "delamination", as applied in this study, is defined as the region in the strengthened RC structure, where there is no contact between the concrete substrate and strengthening FRP sheet.

A significant amount of research related to fatigue of reinforced concrete structures has been carried out; but very little work has been carried out to study the fatigue performance of FRP sheet strengthened RC beams (Mohsen and Thomas, 1998; and Richard and Geoffrey, 1999). No work that the authors are aware of has been conducted to investigate bond performance related to installation defects such as delaminations under the combined effect of fatigue loading and wet-dry cycle. This study investigates this important issue on the influence of induced delaminations on the fatigue performance of FRP strengthened RC beams in the presence of wet-dry cycles.

3. RESEARCH OBJECTIVES

At present there are no guidelines available regarding the permissible delamination sizes in FRP strengthened RC structures. ACI Committee 440 has made unpublished recommendations regarding the size of the delaminations i.e. delaminations of area less than 1,300-mm^2 can be ignored and delaminations of area greater than 16,000-mm^2 should be replaced with new sheet, while the delaminations of dimensions in between the two limits need to be epoxy injected. It should be noted that ACI Committee 440's recommendations regarding the delamination sizes are considered for publication.

The main objective of this study is to investigate the adaptability of the recommendations of the ACI Committee-440 regarding the tolerable delamination size and examine the growth in delamination in FRP sheet strengthened RC beams, when subjected to the combined effect of fatigue and wet-dry cycles. Specifications regarding lap splice requirements for CFRP sheets under static loading are available (Mbrace Composite Strengthening System Design Guide, 1998). This study will also address the issue of minimum lap splice requirement for CFRP sheet to sustain fatigue loading.

4. DESCRIPTION OF EXPERIMENTAL PROGRAM

Four RC beams (250×150×3100-mm) were fabricated in the laboratory with the reinforcement configuration illustrated in Figure 1. The bottom flexural reinforcement consisted of three 9-mm diameter bars providing a total cross section of 71-mm^2 and the top flexural reinforcement consisted of two 9-mm diameter bars providing a total cross section of 47-mm^2. This quantity of steel is slightly higher than the minimum value prescribed for flexural reinforcement by the ACI 318-99 (ACI 318). Stirrups made of 6-mm diameter rods were used at a spacing of 150-mm to provide adequate shear reinforcement. CFRP sheet was used to strengthen the beams. The CFRP sheets are 200-mm wide and 0.16mm thick and are placed throughout the length of the beam. The dimension of CFRP sheet was selected to guarantee yielding of the reinforcing steel in tension followed by concrete crushing without the rupture of CFRP sheet at ultimate load. The test beams differed only in the size of the delaminations they contained; first beam contained delaminations of size 150-mm in diameter, the second beam had delaminations of size 100-mm in diameter and the third beam contained delaminations of size 50-mm in diameter. The circular delamination of size 150-mm represented a size of 18,241 mm^2 that is slightly higher than the worst-case delamination size of 16,000 mm^2. The idea of providing three different sets of sizes of delamination is to investigate the role of size of the delamination as a variable. An additional beam was fabricated without delaminations to serve as reference beam. Each of the strengthened beams was pre-cracked prior to the installation of laminates.

The test results from beam with largest delamination size indicated that delaminations of these sizes have minimal effect on fatigue performance of CFRP strengthened RC structures. Hence, the beams with smaller size delaminations were used to investigate the minimum lap splice length required for CFRP sheets to sustain fatigue loading.

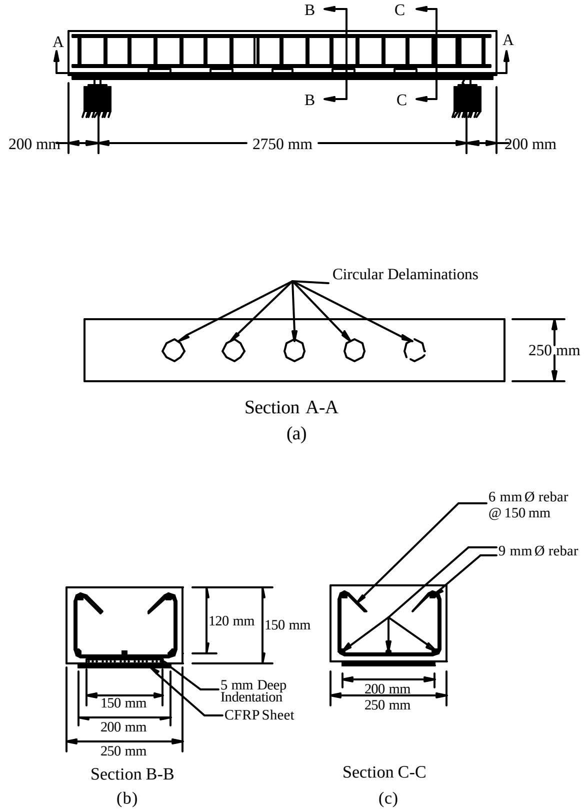

Figure 1. Geometric Details and Configuration of Test Beams

In the beams with induced delaminations of 100-mm and 50-mm diameter, the CFRP sheet at mid-span was cut throughout its width. A new CFRP sheet of width 200mm was epoxied to the existing CFRP sheet with a lap splice of 50-mm on one side of the cut and 150-mm on the other side of the cut in the beam containing delamination of size 100-mm in diameter. A lap splice length of 75-mm on one side of the cut and 150-mm on the other side of the cut was provided in the beam containing the delamination of size 50-mm in diameter. The minimum lap splice length required for CFRP sheets to develop full tensile capacity under static loading is 50-mm (Mbrace© Composite Strengthening System Design Guide, 1998). To investigate if the same lap splice length, required under static loading, is sufficient to withstand fatigue loading, the minimum lap splice length of 50-mm was selected in this study.

Indentations of 5-mm deep and 150-mm in diameter were created at the bottom faces of the test specimens at various locations along the length of the beam. These indentations, shown in Figure 1 (b), served as the regions of delamination between the CFRP sheet and concrete substrate. After 28 days of normal curing and drying, the bottom face of the specimens was prepared to attach CFRP sheet. CFRP sheet was bonded to the tension face of the beam using an epoxy resin throughout the length of the beam as shown in Figure 1. The location of delaminations and the position of strain gages in rebars and CFRP sheet are shown in Figure 2.

A hollow copper tube was placed in the beam with one of its open end in the delamination region and its other open end projecting out of the top surface of the beam. This tube acted as a conduit for the passage of salt water to the region of delamination. As salt water is more corrosive than ordinary water and closely simulates the de-icing salt solution applied on high way bridge decks, the delamination region was subjected to wet-dry cycle using saltwater to simulate the situation that occur in a highway bridge deck or girder.

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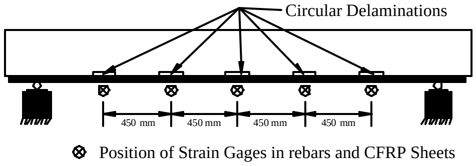


Figure 2. Delamination and Strain Gage Position

The properties of the material used for the fabrication of the specimens are shown in Table 1.

Table 1. Material Properties

Material	Yield Strength (MPa)	Ultimate Strength (MPa)	Young's Modulus (MPa)
Steel rebar	358	537	2 × 105
CFRP sheet	NA	3790	2.3 × 105
Concrete	NA	34	27,770

5. TEST SETUP AND PROCEDURE

All beams were tested in three-point bending configuration with a simply supported test span of 2750-mm. The fatigue loading on beams was stopped when either the specimen failed or after 2 million cycles, whichever occurred first. Highway bridges experience a very low rate of fatigue cycles, usually of the order of 0.1-1 Hz depending on the location of the bridge. Since it is impossible to duplicate the real life fatigue-loading situation, continuous, accelerated fatigue tests are conducted in the laboratories. A frequency of 3-5 Hz is practical and high enough to reduce the testing time; however test results involving higher frequencies need to be carefully interpreted as higher frequencies produce undesirable heating of the specimen. Studies indicate that frequency of loading between 1 Hz and 15 Hz has very little effect on fatigue life of concrete and steel (ACI Committee 215). Statistics about vehicular traffic across the world indicate that a highway bridge experiences 2 million fatigue cycles during its life period of approximately 40 years.

A sinusoidal loading, ranging from a minimum of 10.4 kN to a maximum of 19.3 kN, at a frequency of 3 Hz was used in this study. The minimum and maximum loadings corresponded to 31% and 58% of the ultimate moment carrying capacity of the beam. The above said loading range was chosen to simulate the magnitude of dead load and dead load plus service load that occurs normally on a highway bridge deck or girder.

While the fatigue loading was being applied, salt-water solution (a solution containing 15% of Sodium chloride and 85% of water by weight) was poured periodically through the horizontal copper tubes to simulate the effect of wet-dry cycles. Out of the five delaminations present in the test specimen, three were subjected to a combined fatigue loading and wet-dry cycles while the other two delaminations were kept all the time dry throughout the test. Static tests were conducted at the beginning of the test and after 5000, 100000, 500000, 1000000 and 2000000 cycles. During the pseudo static test, the deflection at mid-span was measured using LVDT and the strains in the rebar and CFRP sheet were measured using strain gages. All the measured quantities, including the load, were recorded in a computer through an automatic data acquisition system.

The delaminations were monitored for their growth in size periodically using thermography techniques. Thermography is a nondestructive technique used to detect debonds in laminates and composite structures. Thermographic technique can be used effectively in detecting the presence of the delamination between concrete and FRP sheet. Thermography uses the principle of variation in heat conduction property produced by the presence of delaminations. If the FRP bonded concrete containing delamination is heated, the delamination area will conduct the heat slowly than other areas. This difference in heat conduction property produced by the presence of delaminations is recorded using an infrared camera. The infrared camera produces images of the delamination which appears as "hot spots" on a relatively "cool" background.

6. TEST RESULTS AND DISCUSSION

The reference beam and the beam with delamination size of 150-mm in diameter showed adequate structural performance even after 2 million cycles. The beam with 50-mm lap splice length failed after 286,930 prematurely due to the slipping and eventual debonding of CFRP sheet in the lap splice region. The beam with 75-mm lap splice length completed 2 million cycles with no damage in the lap splice region.

Mid-span deflection, crack width and the size of the delamination region were monitored during the course of fatigue test. The performance of each beam in terms of stiffness, crack widening with number of cycles and fatigue life and delamination growth are discussed below.

6.1 Stiffness

Stiffness is defined as the slope of the load – deflection relationship at mid-span. In Figure 3, mid-span deflection is plotted against the applied load during the static test for the reference beam. The initial stiffness and final stiffness after 2 million cycles of fatigue loading of the reference beam was calculated to be 1.36 kN/mm and 1.25 kN/mm respectively. There was a stiffness reduction of approximately 8% for the reference beam.

Figure 4 illustrates the load-deflection curve for the CFRP strengthened RC beam with 150-mm diameter delamination. The stiffness reduction after 2 million cycles was approximately 4%.

Figure 5 illustrates the load-deflection curve of the beam containing 50-mm lap splice. The stiffness reduction of this beam, after 100,000 cycles, was significant, approximately 40%. This beam experienced the highest stiffness reduction. As noted previously, this beam failed in the lap splice region after 286,930 cycles. Figure 6 illustrates the stiffness degradation for the beam with 75-mm lap splice length that was found to be approximately 13%.

6.2 Fatigue Life of lap spliced specimen

The beam repaired with a lap splice length of 50-mm survived only 286,930 cycles and failed by separation of the epoxy at the sheet interface level (i.e. lap splice CFRP sheet to existing CFRP sheet); the extent of separation (debonded length) was throughout the entire lap splice length of 50-mm upon failure. The beam with 75-mm lap splice sustained 2 million cycles of fatigue loading with a stiffness degradation of approximately 13%. The fatigue life of beam with lap splice length of 75-mm is higher than the fatigue life of beam with 50-mm lap splice length; this indicates that a lap splice length of 50-mm is insufficient for CFRP sheets to sustain fatigue loading of 2 million cycles.

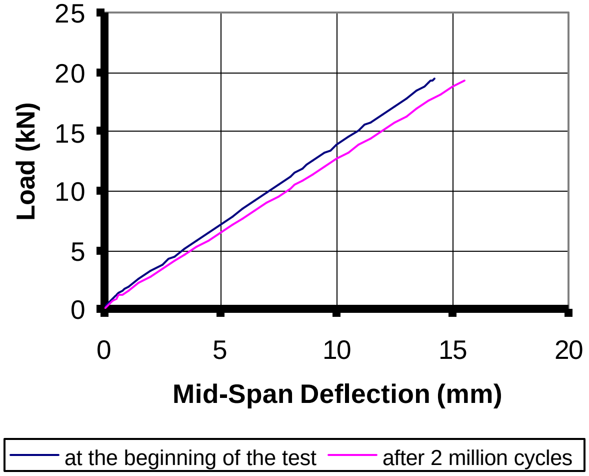


Figure 3. Load versus Mid-Span Deflection of the Reference Beam

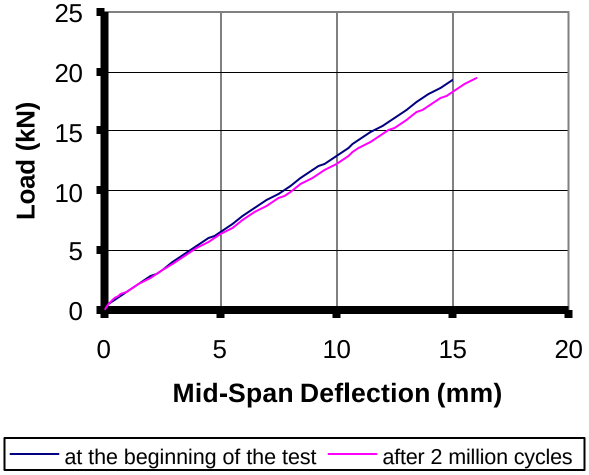


Figure 4. Load versus Mid-Span Deflection of the beam with 150-mm Delamination

6.3 Delamination Growth

The delaminations, in the beam with delaminations of size 150-mm in diameter, were monitored using thermographic techniques and photographed by an infrared camera. The growth of delamination at the mid-span that was subjected to combined effect of fatigue and wet-dry cycles and maximum loading was monitored. Thermograhic images of the delamination were obtained before conducting pseudo static test. Figure 7 shows the thermographic images of the delamination at the beginning of the test and after 2 million cycles.

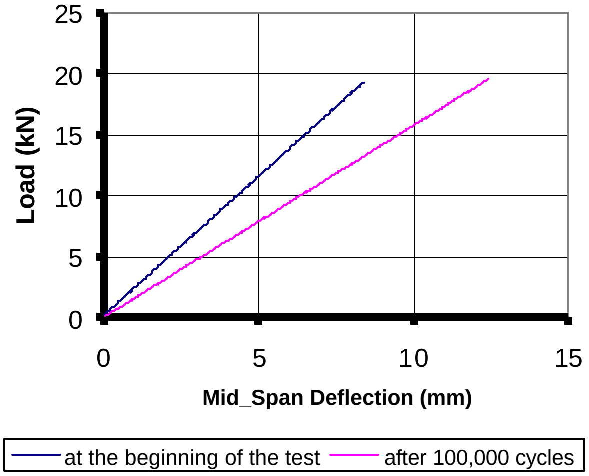


Figure 5. Load versus Mid-Span Deflection of the beam with 50-mm Lap Splice

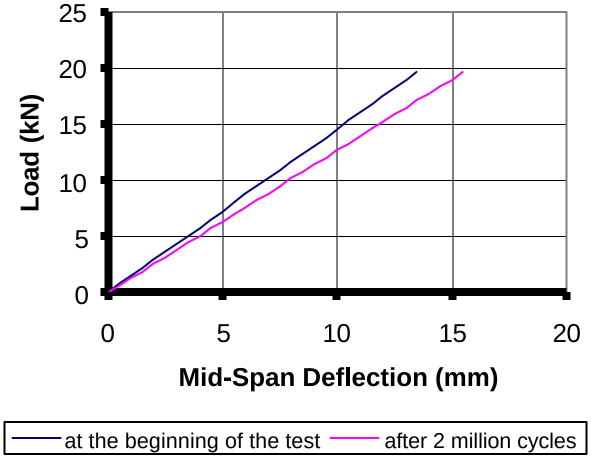
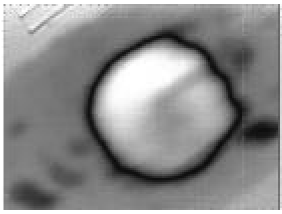
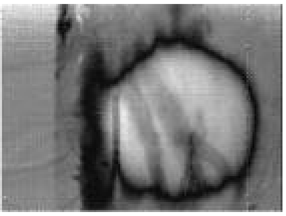


Figure 6. Load Versus Mid-Span Deflection of the beam with 75-mm Lap Splice

A calibrated scale, available in the software package DELTATHERM®, was used to measure the size of the delamination and it was noted that there was no significant growth in the delamination after 2 million cycles. The increase in area was approximately 5%. It was also noticed that the delamination extended randomly; the smudges in Figure 7(b) represent the region of extension of delamination. The delamination region does not appear to be a perfect circle due to the oozing of epoxy resin along the edges of the indentation occurring during installation of the sheet.



7 (a). Thermographic Image Prior to Fatigue Cycling



7 (b). Thermographic Image after 2 Million Cycles

6.4 Crack width

Increase in deflections and crack widths of reinforced concrete beams subjected to cyclic loading can be significant (Balaguru and Shah, 1982). In this study, the crack width of a pure flexural crack was monitored and measured continuously with the help of a hand held, portable microscope while conducting pseudo static tests. The crack width corresponding to the maximum load of fatigue cycle, before the beginning of the cyclic load application, was recorded to be 0.254-mm for the reference beam, 0.305-mm for the beam having the circular delamination size of 150-mm in diameter and 0.381-mm for the beam with the delamination sizes of 100-mm and 50-mm in diameter. There was no increase in crack width, corresponding to the maximum load of the fatigue cycle, throughout the course of fatigue loading in all the beams. In ordinary reinforced concrete beam, the crack widths significantly increase with fatigue cycles; but in CFRP strengthened reinforced concrete beams there was no increase in crack widths with the number of fatigue cycles.

7. CONCLUSION AND FUTRE RECOMMENDATION

1. Installation defects such as delaminations, up to 18,241-mm^2 representing a circular area of 150 mm in diameter, have no significant effect on the performance of CFRP strengthened RC beams in terms of stiffness of the beam. Hence, based on data from one test specimen, ACI Committee – 440's recommendation that delaminations more than 16,000-mm^2 need to be replaced with new sheet is conservative.
2. There is an insignificant increase in area, approximately 5%, of delamination of size 18,241-mm^2 when subjected to the combined effects of 2 million cycles of fatigue loading and wet-dry cycles.

However, the small increase in area of delamiantions has no effect on fatigue performance.

3. A lap splice length of 50-mm, between CFRP sheets, at critical section does not survive until the desired 2 million cycles. While providing 50-mm lap splice length in CFRP sheets is safe under static conditions, CFRP sheets need more lap splice length in structures that resist fatigue loading. A lap splice length of 75 mm satisfactorily sustained 2 million cycles of fatigue loading.
4. More tests need to be conducted to verify the repeatability of test results.
5. Other environmental exposure tests under fatigue cycling are also recommended to examine the combined effects on lap splices and delaminations. Field monitoring projects are also recommended to further study these effects under actual field conditions.

8. ACKNOWLEGEMENT

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