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Finite Element Assessment on Bond Behavior of FRP-to-Concrete Joints under Cyclic Loading

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Abstract**—**Over the last two decades, externally bonded fiber reinforced polymer (FRP) composites bonded to concrete substrates has become a popular method for strengthening reinforced concrete (RC) highway and railway bridges. Such structures are exposed to severe cyclic loading throughout their lifetime often resulting in fatigue damage to structural components and a reduction in the service life of the structure. Since experimental and numerical results on the fatigue performance of FRP-to-concrete joints are still limited, the current research focuses on assessing the fatigue performance of externally bonded FRP-to-concrete joints using a direct shear test. Some early results indicate that the stress ratio and the applied cyclic stress level have a direct influence on the fatigue life of the externally bonded FRP. In addition, a calibrated finite element model is developed to provide further insight into the influence of certain parameters such as: concrete strength, FRP thickness, number of cycles, frequency, and stiffness on the fatigue life of the FRP-to-concrete joints.

Keywords**—**FRP, concrete bond, control, fatigue, finite element model.

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I. INTRODUCTION

THE use of Fiber Reinforcement Polymer (FRP) composite material became very widespread in use for several application in many existing reinforced concrete structures. Technically, these composite materials proved an excellent performance of rehabilitation and strengthening structures due to its well properties of high tensile strength, resistance to harsh environment, and easy to install. One of the most successful FRP application raised recently is the externally bonded FRP reinforcement which has been carried out more in railway bridges and showed ideal outcomes in strengthening and repairing of reinforced concrete component. In spite of the great advantages of FRP strengthening systems, premature debonding still the key factor preventing full utilization of the tensile strength properties of the FRP material

The main problem with bonding and debonding is the mechanism and mode of failure that can occur between the FRP and the concrete. Extensive research has been conducted to set design guide lines, illustrating that the bond strength of FRP laminates can be improved when adequate anchorage is provided, resulting in a delay of debonding failure [1]. As a result, numerous research have been implemented to use the anchorage devices or joints that showed significant impact on mitigating the longitudinal shear stresses and peeling stresses that often initiated at fiber termination points inducing premature debonding failure of FRP-to-concrete joints [2].

All highway and bridges experience very high number of cyclic loading during their service life, which leads the fatigue damaged to be occurred. Some research studies showed that anchoring the ends of the CFRP plate or fabric sheet can provide a higher strain in the FRP composite prior to debonding and allow a higher degree of strengthening to be achieved using less material [3].

The experimental and numerical analysis to quantify the fatigue performance of FRP-to-concrete joints is still considered in the shortage list in the design guidelines. This paper is part of a PhD research on investigation the performance of FRP anchorage devices in RC bridge beams subjected to cyclic loading. The work consists of using externally bonded FRP-to-concrete joints anchored with and without bidirectional fabric patch anchors. The study plan set will investigate the influence of stress amplitude, number of cycles, sequence of cyclic loading, and frequency of loading on the fatigue life of the joints. The test results will be presented in a form of S-N curves, relating the stress amplitude to the logarithm of the number of cycles. Up to now, the FEM has been achieved to verify the fatigue behavior on the first model without bidirectional fabric (Unanchored-Control model). Full details of the proposed model and its results are presented in the following sections.

II. EXPERIMENTAL WORK

A. Specimen Design

To achieve the research objective, an experimental program was designed using a near end supported single shear pull test setup. Several identical specimens of reinforced concrete block of dimensions (400×400×250mm) consisting of FRP-to concrete joints were used. The blocks were reinforced nominally with 4-Φ12 diameter bars at 120mm centers on each face. 30mm of the reinforcement cover was used. Specimen had included a single laminate strip dimensions (800×120×1.4 mm) bonded to the surface of the concrete block with a bond length of 370mm.

B. Material Properties

Material properties supplied by the manufacturers' specifications can be found in details in [4]. However, it has been used with further development and verification experimentally on its parameters which then considered in this numerical assessment as summarized in Table I.

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C. Experimental Setup

The testing rig that used in this experimental program is shown in Fig. 1. Further details of its construction and configuration are presented in [5]. The test rig was used to assure the concrete block can site properly inside the MTS machine of 1MN.

D. Test Preparation

Special test preparation was used before applying the FRP application. This included adequate preparation of the concrete surface by sandblasting, water jetting, and well vacuum cleaning. This step is highly recommended by many previous research studies as it has a significant influence on the accuracy of the result depending on the performance of the bond behavior of FRP-to-concrete joints. Further details of material constructions can be found in [6].

III. THE PROPOSED FINITE ELEMENT MODEL

Simulation analysis of finite element model has become very significant technique that give an indication about the results prior to experimental work, by predicting some parameters that help to decrease the number of tests required and can be more beneficial in terms of saving money and time. The proposed model was implemented in ATENA package of FEM for non-linear structure analysis [7]. The model was setup to build the actual specimen components (concrete block and FRP materials). The mode of failure simulated between the CFRP laminate and the concrete surface was identified as cracking in concrete near the bonding area, using very fine mesh size of (0.005m). The main reason of this simulation analysis is to construct a calibrated numerical model that can be used to provide further understanding into the mechanisms of fatigue damage of FRP to concrete joints as a result of cyclic loading. Parametric studies using a calibrated model can provide further insight into the influence of certain parameters such as concrete strength, FRP thickness, geometry, number of cycles, frequency and stiffness. Moreover, the outcomes obtained from the FEM will also be compared with those from the experimental work in order to see the agreement in data results. Several attempts have conducted over the last year by applying monotonic loading on the control model. This followed by a series of cyclic loadings using various parameters. The method will be illustrated in details in the following sections.

A. Model Parameters

The proposed model covered different parameters that have a significant influence on model calibration in terms of material used. The materials used are classified into four major categories; these are: concrete block, CFRP laminate, laminate adhesive, and the interface layer between the concrete and the adhesive. The bond length used was (370mm) applied over the four layers mentioned above. The adhesive and the CFRP laminate were simulated as per manufacture's specification (MBRACE) with a thickness of (1.5 and 1.4m) respectively. The compressive strength value of the concrete is considered one of the major key that many parameters depend on, and therefore, a high strength of concrete was used in this assessment with a mean compressive strength f_c' (69MPa) to assure the mode of failure occurs over the bonding area between the concrete and the FRP applications. This compressive value was simulated and verified with experimental data using standard compression test of cylinder (100*200mm), where same material of concrete batch used. The other important factor on performing this assessment is the facture of energy, where the proposed model was calibrated based on a nonlinear plasticity fracture material explained somewhere else in [8], however; in this case it assumed as (125N/m).

TABLE I
MATERIAL PROPERTIES AND MODEL PARAMETER USED IN FEM

Properties	Concrete block	CFRP Laminate	Adhesive
Compressive Strength, fc′ (MPa)	69	-	-
Tensile Strength, FT (MPa)	5	3300	-
Young's modulus, Es (MPa)	42.010	200,000	10,000
Poisson ratio, ν	0.2	0.42	0.4
Fracture energy, GF (N/m)	125	-	-
*Beta Fatigue	0.09	-	-
Yield Strength, YS (MPa)	-	-	21.3

*Beta Fatigue, β, tensile fatigue of concrete that can be determined from the slope of the Wöhler (S-N) curve for the stress-based contribution [9]. It is assumed as 0.08 by [10], however; in this case it has been considered as 0.09.

Fig. 1 Control specimen inside the 1MN machine

B. Geometry and Mesh Size

The model was built as axis-symmetric from the center line in a way that represents half of the actual specimen in order to mitigate the analysis time of the boundary conditions. The mesh size of the microelements was refined more to be (0.005m) so the modes of failure can be clearly seen in the concrete block and particularly near the bonding area as shown in Fig. 2. The geometry of the material used are demonstrated in Fig. 3.

IV. RESULTS

To verify the research objectives, the plan was set to have a matrix of fatigue tests that can establish reliable S-N curves, clarifying the fatigue performance of FRP-to-concrete joints. The method used to conduct some monotonic tests and record its ultimate failure load to be used for comparing with FE result. Afterwards, the stress amplitude can then be calculated as a percentage of the ultimate failure load obtained from the static test. However, at this stage only monotonic tests were performed in the laboratory on identical RC blocks, using a direct shear test method applied to the end of the CFRP laminate. Regarding to this assessment with FEM, only two blocks result are presented. It has been found that the maximum failure load obtained from the machine for those two blocks were (115 and 113 kN) respectively. Two strain gauges were attached onto the laminate surface on both faces at specific location to measure the bond slip that might occur to the laminate during the test as a result of the applied load. Fig. 4 shows the load versus micro-strain for the first block, where the max strain reached was (4180με) at failure load of (115kN). It can been noticed that the trend of the two strain gauges showed very good convergence with almost linear increasing, which indicates that no clear bending happened during this test. On the other hand, the second specimen showed that the maximum strain reading recorded was (3645 με) at failure load (113 kN). The two strain readings of the second block showed a clear divergence in their trend which verified that bending in the laminate was occurred during the loading test as shown in Fig. 5. Despite the maximum failure load measured of both specimens are very close, the difference in strain gauge reading was about (5%). This confirmed the effect of bending in CFRP laminate that happened in the second test.

Regarding the FEM static result, using the same material properties considered in the experimental load, the result showed that the ultimate failure load measured was (118kN), which demonstrates excellent correlation with those results obtained from the experimental work as shown in Fig. 6.

The second stage of this work was to implement a series of cyclic loading on this model so it can be helped to predict the fatigue life of externally bonded FRP-to-concrete joints. In this paper, two trials of fatigue test were conducted. These trials are representing the amplitude range of the maximum and minimum stress load, which have been taken as (30-80% and 40-80%) of the ultimate static load recorded from simulation analysis (118 kN). The test consists of applying a static load up to 50% of the ultimate static load and then unloaded to 30%, followed by a cyclic loading until the model failed. The first cyclic test run for a range of (30%-80%) until the fatigue failure occurred at 2,520,000 cycles as shown in Fig. 7. Furthermore, when this compared to the static test, a perfect compatibility of elastic behavior was found as shown in Fig. 6. It has been found that the max displacement reading observed during the cyclic test was almost cyclizing between (0.7 to 1.7 mm) until 2,520,000 cycles. Since after, the displacement remained increasing over the period of post fatigue until it reached (3.4 mm) at 2,640,000 cycles (Fig. 8). Furthermore, a second cyclic test was implemented using the same technique considered in the first test but this time for an amplitude range of (40%-80%). It can be seen the model failed after 4,000,000 cycles, which is double than the cyclic failure recorded in test 1. Fig. 9 demonstrates the fatigue loading for test 2, while the logarithm cyclic pattern can be seen in Fig. 10.

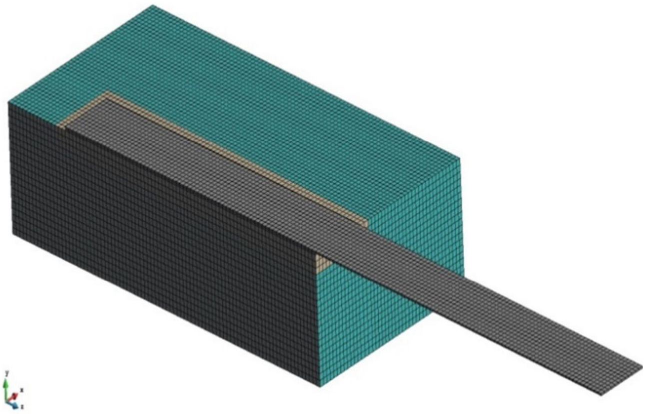

Fig. 2 Refine of Mesh size used to monitor the mode of failure

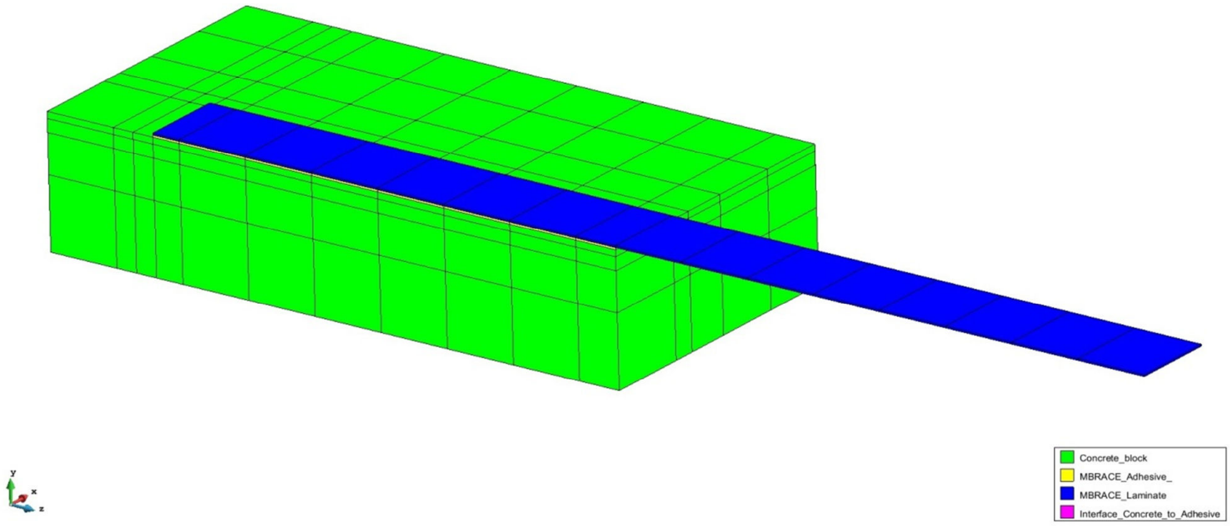

Fig. 3 Geometry of the control mode

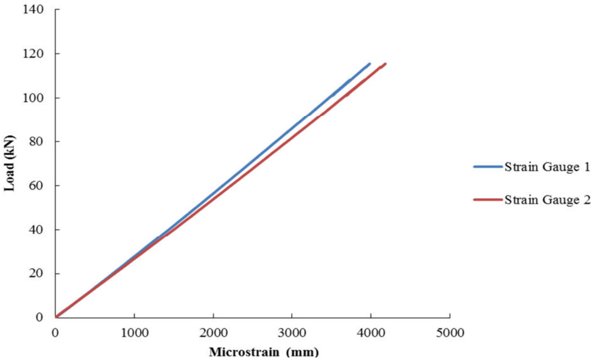

Fig. 4 Load vs. Micro-strain (Block 1)

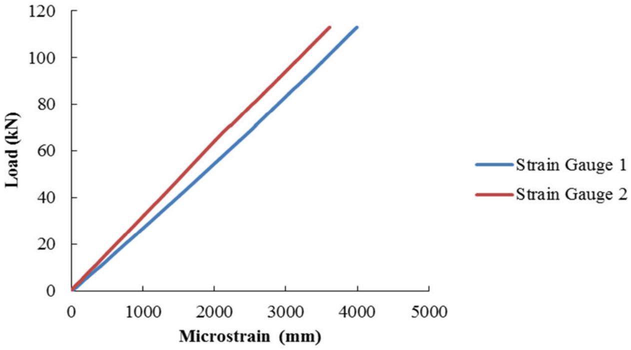

Fig. 5 Load vs. Micro-strain (Block 2)

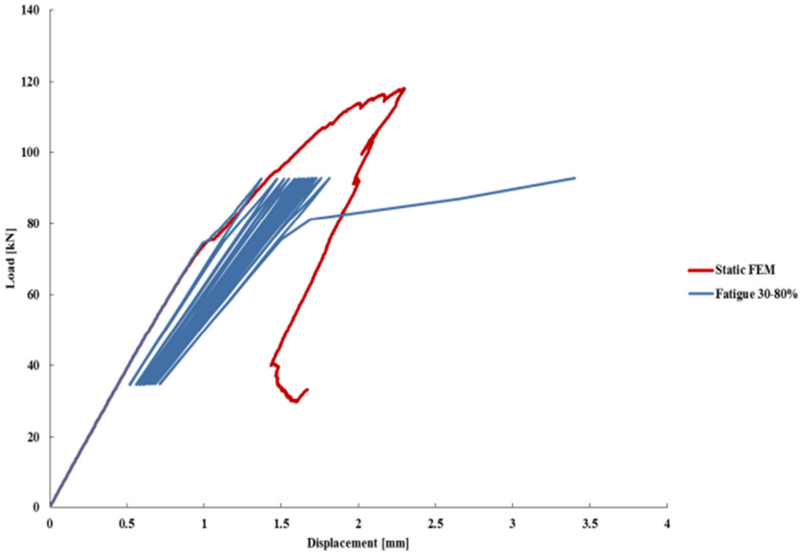

Fig. 6 Load vs. displacement (30%-80%)

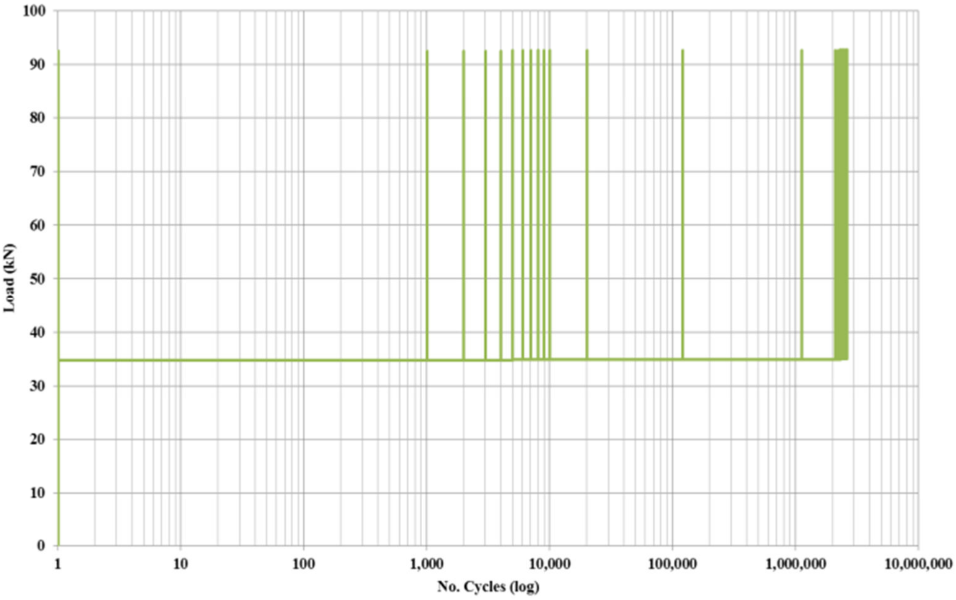

Fig. 7 Load vs. No. of Cycles (30%-80%)

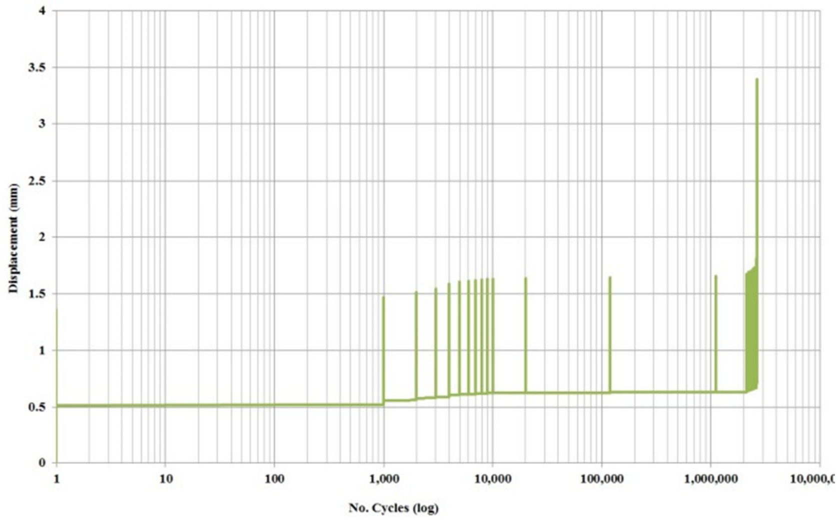

Fig. 8 Displacement vs. No. of Cycles (30%-80%)

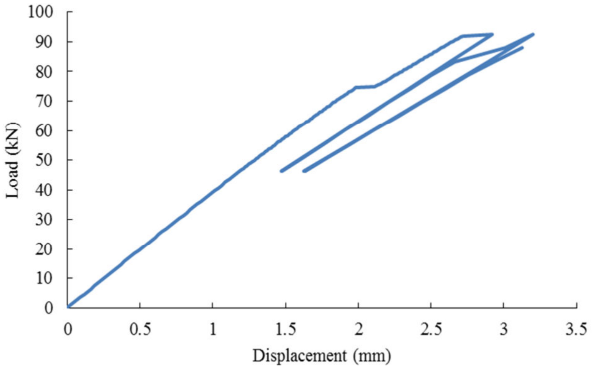

Fig. 9 Load vs. displacement (40%-80%)

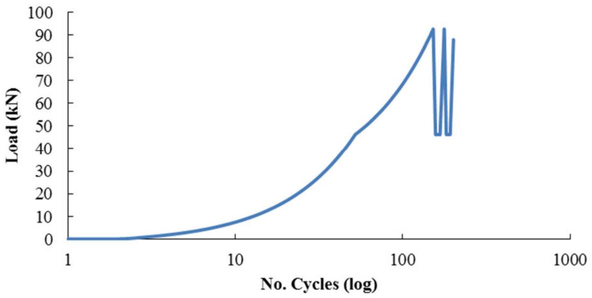

Fig. 10 Load vs. No. of Cycles (40%-80%)

The max displacement recorded in this test was (3.2mm) which is very close to the displacement value achieved in test 1 with (3.4mm). This can be clearly noticed in Fig. 11.

As the concrete parameters are very important of indicating the mode of failure, the tensile strength value obtained from the experimental work (5MPa) provided satisfactory agreement in FEM simulation as shown in Fig. 12, where the mode of failure observed between the concrete and the CFRP laminate (bonding area).

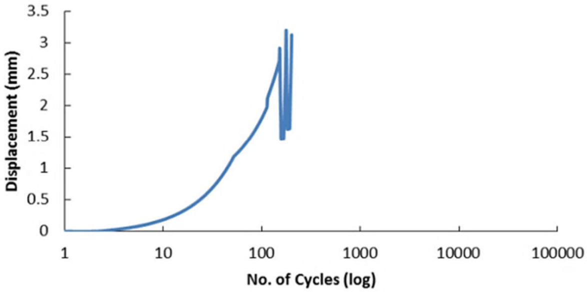

Fig. 11 Displacement vs. No. of Cycles (40%-80%)

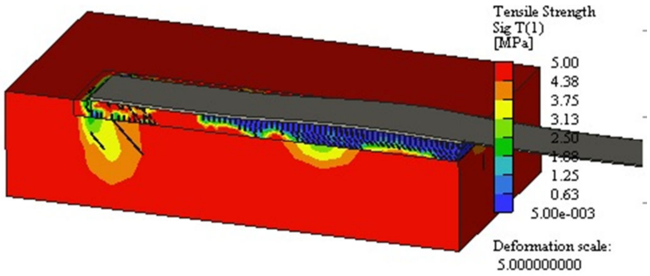

Fig. 12 Mode of failure (Tensile strength)

V. CONCLUSION

The main reason of this simulation analysis was to construct a calibrated numerical model that can be used to provide further understanding into the mechanisms of fatigue damage of FRP to concrete joints as a result of cyclic loading. Numerical simulation analysis of FEM approach used to acquire more data by conducting parametric studies that can give more insight into the influence of certain parameters such as concrete strength, FRP thickness, fracture energy, and stiffness. It is decided to begin with FEM before performing the experimental work as this step can save more money and time when doing the actual test. The assessment showed that using the same material properties considered in the experimental work and correspond them in the proposed FEM, the result presented excellent agreement on the monotonic test

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between the experimental data and the FEM with average maximum failure load of (114 kN) and (118 kN) respectively. Furthermore, the fatigue test that successfully calibrated on the FEM provided better grasp on the principle of fatigue test overall and drawn a clear expectation on the fatigue damage at certain number of cycles. The FE results found that fatigue test conducted on the control model failed after (2,520,000 cycles and 4,000,000 cycles) for the stress amplitude range of (30-80% and 40-80%) respectively. This is very good outcome that can be considered when implementing the fatigue experimental work so it can be used to see how far the fatigue damage can be occurred compared to the data gained from the FE results. Depending on the future experimental fatigue test, further parameters that have big impact on the fatigue performance can then be investigated such as; the influence of stress amplitude, number of cycles, sequence of cyclic loading, and frequency of loading. It is expected that the well-planned experimental investigation coupled with the verification of the advanced numerical analysis will provide a better prediction model of the debonding failure load under fatigue conditions. A set of guidelines can then be proposed for debonding prevention and explore for further research.

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REFERENCES

[1] Galal, K. and A. Mofidi, Shear strengthening of RC T-beams using mechanically anchored unbonded dry carbon fiber sheets. Journal of Performance of Constructed Facilities, 2009. 24(1): p. 31-39.

[2] Al-Mahaidi, R. and R. Kalfat, Investigation into CFRP laminate anchorage systems utilising bi-directional fabric wrap. Composite Structures, 2011. 93(4): p. 1265-1274.

[3] Kalfat, R., R. Al-Mahaidi, and S.T. Smith, Anchorage devices used to improve the performance of reinforced concrete beams retrofitted with FRP composites: State-of-the-art review. Journal of Composites for Construction, 2011.

[4] Kalfat, R. and R. Al-Mahaidi, Finite element investigation into the size effect of bidirectional fibre patch anchors used to enhance the performance of FRP-to-concrete joints. Composite Structures, 2015. 121: p. 27-36.

[5] Kalfat, R. and R. Al-Mahaidi, Investigation into bond behaviour of a new CFRP anchorage system for concrete utilising a mechanically strengthened substrate. Composite structures, 2010. 92(11): p. 2738-2746.

[6] Kalfat, R., R. Al-Mahaidi, and G. Williams, Investigation of Efficient Anchorage Systems for Shear and Torsion Retrofitting of Box Girder Bridges. ACI Special Publication, 2011. 275.

[7] Červenka, V. and L. Jendele, ATENA Program Documentation Part. 2000.

[8] Kalfat, R. and R. Al-Mahaidi, Finite Element and Experimental Investigation into Patch Anchor Sizes Used to Enhance the Bond Performance of FRP-to-Concrete Joints. Special Publication, 2015. 301: p. 1-16.

[9] Dobromil, P., C. Jan, and P. Radomir, Material model for finite element modelling of fatigue crack growth in concrete. Procedia engineering, 2010. 2(1): p. 203-212.

[10] Taerwe, L. and S. Matthys, Fib model code for concrete structures 2010. 2013: Ernst & Sohn, Wiley.