AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
STRUCTURAL ENGINEERING DEPARTMENT

BOND BEHAVIOR OF CONCRETE BEAMS STRENGTHENED WITH EXTERNALLY BONDED FIBER REINFORCED LAMINATES

A Thesis
Submitted in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY
in
CIVIL ENGINEERING (STRUCTURES)

by

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STATEMENT

This thesis is submitted as partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering (Structures), Faculty of Engineering, Ain Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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SUMMARY

The research program presented in this thesis is of multi phases to evaluate and characterize the bond and load transfer mechanisms between FRP materials and concrete and to investigate the influence of various parameters on the debonding process. A comprehensive investigation is conducted in four phases.

The first phase involves the collection and compiling of experimental data to create wide spectrum databases for simply supported RC beams strengthened with FRP laminates that experienced either plate end (PE) or intermediate crack (IC) debonding failure. Two databases are constructed: one for beams failed in PE debonding, and another database for beams exhibited IC debonding. The second phase introduces the existing design methodologies used for the evaluation of the FRP bond strength: empirical formulas, mechanics of materials models, fracture mechanics approaches, in addition to design formulas in various codes and design guidelines. The third phase comprises a non-linear finite element (FE) analysis to predict the debonding failure loads/strains of the data gathered from the literature. The FE analysis is employed to set up a clear methodology for modeling FRP-strengthened beams; especially the FRP-concrete interface. The fourth phase presents a parametric study of 38 simply supported RC beams strengthened with externally bonded FRP sheets with variable parameters and analyzed using the non-linear FE program. The study aims to investigate the influence of key parameters believed to affect the behavior of FRP-strengthened concrete structures.

Finally, a comparison is held among the experimental data, the existing design methodologies, the design formulas in various design guidelines, and the non-linear FE analysis. The assessment aims to highlight the most efficient models in predicting debonding failure load. Based on the statistical analysis outcomes, the American design guideline (ACI Committee 440-2008) is considered the least scattered and the most efficient model for predicting debonding failure loads, but with un-conservative nature.

The design recommendations and guidelines are proposed based on the results of this comparison and the parametric study that is conducted in light of the non-linear finite element results. According to the research findings, the strain level, at which debonding may occur, has been identified through a proposed analytical expression. The model is introduced to predict the behavior of RC beams strengthened in flexure with externally bonded FRP laminates and verified with the gathered databases.

Keywords: RC beams; FRP composites; Debonding; Test database; Finite element method; Analytical models; Statistical analysis; Strengthening design.

To fulfill the previously mentioned objectives, this research is divided into the following chapters:

- Chapter (1) is an introduction to this study. This chapter discusses the importance of the research and highlights the scope of the research program.

- Chapter (2) illustrates the use of the advanced composite materials to strengthen concrete structures through a literature survey and highlights the commonly used retrofitting materials, properties, and application procedures. A review of the existing analytical models available in the literature and various design guidelines to predict PE and IC debonding

failure loads is included. The contents are placed within the framework of the knowledge and the aim of this thesis.

- Chapter (3) presents the compiled databases. This part of the thesis proposes a PE debonding database, an IC debonding database, the selection criteria, and a brief on the experimental studies enclosed in each database.

- Chapter (4) introduces a description of the non-linear FE program utilized to simulate the RC beams strengthened in flexure with externally bonded FRP laminates and contained in the collected databases. The FE description includes types of elements, material definition, contacts characterization, solution strategy, failure criteria, loading, and boundary conditions. This section of the research covers the FE results obtained from the program and a discussion of the results.

- Chapter (5) provides an assessment of the existing PE debonding analytical models as well as different design guidelines with the test data included in the gathered PE database. This part of the study highlights the significant results of a comprehensive statistical comparison between the PE experimental data, the current PE design methodologies, and the non-linear FE results of the beams involved in the PE database.

- Chapter (6) presents an assessment of the available IC debonding analytical models and design guidelines with the test results enclosed in the assembled IC database. This section of the dissertation summarizes the primary outcomes of a detailed statistical study held among the IC experimental data, the existing IC design methodologies, and the non-linear FE results of the beams in the IC database.

- Chapter (7) includes a parametric study conducted on a constructed database analyzed using the non-linear FE program. This chapter investigates the influence of different parameters on the bond strength of retrofitted RC beams and introduces a formula for the prediction of debonding failure loads. The results are formulated into clear design considerations for the application of externally bonded FRP in flexural strengthening to be incorporated in the Egyptian Code of Practice.

- Chapter (8) highlights the general conclusions of the study alongside with recommendations for future research and developments in this subject.

TABLE OF CONTENTS